A SIMULATION METHOD FOR PREDICTING HYDROLOGICAL EFFECTS OF LAND-USE CHANGES

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ABSTRACT

A method was developed to predict the effects of land-use changes on flood hydrograph characteristics, especially the flood peak. It comprises a modified version of the Laurenson (1962, 1964) runoff routing model and employs a sensitivity analysis technique (Burton, 1969). The loss rate parameter in the model is altered to simulate land-use changes.

With only the basic rainfall and streamflow data, the method permits an examination of the hydrological sensitivity of different sub-areas of a catchment to land-use changes. It therefore enables the designer to find that region of a catchment where a proposed land-use change would have the most beneficial effect on the flood hydrograph at the outlet.

Before a fully quantitative prediction can be made a mathematical relationship between the loss rate parameter and the proposed land-use change is normally required. In this investigation a relationship was obtained for the exotic forest land use.

A feature of the investigation was the improvement of the Laurenson model for reproducing flood hydrographs. The isochronal sub-area pattern of the Laurenson model was amended so that the model flow pattern more closely approximates the catchment drainage system. An optimisation procedure was also incorporated in the model for the purpose of deriving the optimum routing equation for the storm concerned.

The modified model and the prediction method are demonstrated using the 780 square mile (2020 km^2) Motueka catchment in New Zealand.

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NOTATION

Symbol		Equation of Origin
A	Coefficient in the reservoir delay time-discharge equation (Eq. 3.11).	3.7
A_s	Area of a sub-area, in square miles.	3.2
B	The exponent in the reservoir delay time-discharge equation (Eq. 3.11).	3.7
c	A routing variable.	3.12
d	The rainfall total of a sub-area rainfall hyetograph, in inches.	5.2
i	A rate of inflow to a reservoir.	3.12
K	Delay time of flow through a reservoir, in hours.	3.10
k_r	Depletion ratio constant.	5.1
L	Catchment lag, in hours.	3.3
L_t	The average travel time for a catchment during a small time increment.	3.1
nr	Number of sub-areas in a catchment that received rainfall.	5.2
q	Used to denote streamflow discharge (e.g. Eq. 3.8) and also a rate of outflow from a reservoir (Eq. 3.12).	
q_D	A rate of direct runoff, in cusecs.	3.4
q_T	A rate of total runoff, in cusecs.	3.4
$\bar{q}_{TD}$	Mean rate of total runoff over the period of direct runoff, in cusecs.	3.4
$\bar{q}_{TS}$	Mean rate of total runoff over the period of surface runoff, in cusecs.	5.5
Y	The abscissa value of the centroid of the dimensionless time-area diagram.	3.1
Δt	Routing period, in hours.	3.13
$\Delta\tau_R$	The difference in relative travel time for the reservoir concerned and the adjacent one downstream.	3.11
τ	Travel time from a point in a catchment to the outlet.	3.1
τ_R	Relative travel time from a point in a catchment to the outlet.	3.1

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Catchment management has been defined (Hewlett and Nutter, 1969) as the management of the natural resources of a catchment primarily for the production and protection of water supplies and water-based resources, including the control of erosion and floods, and the protection of aesthetic values associated with water. One catchment management practice is the alteration of the land use to improve the downstream water quality and quantity characteristics in a catchment. Afforestation, for example, has long been acknowledged as a major form of catchment management in stabilising soil slopes and halting accelerated erosion. There is now also recognition of its dual effect in reducing flood runoff, thereby limiting the flood risk. Alternatively, in regions where water is scarce, a change in land use from forest to grass can be an effective measure in increasing water yields while still maintaining soil stability.

The 1416 square mile (3667 km^2) Waimakariri catchment on the eastern slopes of the Southern Alps in New Zealand has a flood problem. A committee was formed to investigate the likely effects of various land treatments, including the possible afforestation of the whole of the upper catchment to the 3000 ft (915 m) level, in terms of changes at the catchment outlet to water yield, flood peak discharges and water quality. No conclusions were forthcoming on these specific requests, the variability in the available hydrological data being considered greater than the probable resulting streamflow changes.

The possible Waimakariri scheme typifies the types of "physical forecasting" requests that can be made. With an increasing number of similar catchments likely to come under similar scrutiny, there is a clear need for a method which will assist in the prediction of the hydrological effects of land-use changes.

1.2 PREDICTING EFFECTS OF LAND-USE CHANGES

Previous work (see Chapter 2) has made the prediction of the qualitative effects of land-use changes on the flood hydrograph reasonably straightforward. The difficulty is in quantifying the effects. With the work cited in Chapter 2, the quantitative effects of given land-use changes varied with the catchment studied.

One of the causes of the varying responses is the varying hydrological size of the catchments studied. A hydrologically small catchment is one with runoff characteristics primarily determined by the factors which govern overland flow, e.g. high-intensity rainfalls and land use. In hydrologically large catchments the catchment storage is the predominant factor governing the streamflow. It attenuates and translates the flood hydrograph, largely suppressing the effects of land-use changes on the hydrograph shape and peak. The physiography of a catchment, which governs its storage capacity and therefore its ability to mask the effects of land-use changes, uniquely defines each catchment. This uniqueness suggests that each catchment's flood hydrograph response to land-use changes is different and the evidence to date supports this view.

The matter is further complicated by the actual location of the land treatment site. A catchment may contain a number of possible sites with each site located differently in relation to the drainage pattern and, therefore, with respect to the distribution of catchment storage. Hence, one site may exhibit greater sensitivity, in terms of changes in the flood hydrograph characteristics, than another to treatment.

The flood hydrograph response to land treatment depends then, not only on the particular catchment, but also on the location of the treatment within the catchment. The catchment concerned and the particular land treatment site together produce a unique set of storage characteristics. Each problem concerning the effects of land-use changes on the flood hydrograph therefore demands its own individual solution.

1.3 PREDICTION TECHNIQUES

The earliest form of prediction of the effects of land-use changes involved the translation of the observed effects of similar changes in a similar catchment. However, physical similarity does not always imply hydrological similarity. Indeed Lull and Sopper (1967) found there was as much variation between catchments within a physiographical region as there was between regions.

A more objective approach is the use of multiple regression analysis e.g. Anderson (1949). Based on an analysis of experimental data a dependent variable, often flood peak discharge, is mathematically related to a set of independent variables. The latter will include those variables deemed relevant by the researcher. The effect of a land-use change is deduced by altering one or more of the independent variables.

Such an analysis requires a large amount of data, and it has been suggested (Storey et al, 1964) that a minimum of eight catchments should be involved. While the resulting equation can be statistically significant it may give misleading cause and effect relationships. There is also some doubt as to whether it can be applied to other catchments.

Neither of the above prediction techniques, in common with some more elaborate ones e.g. regional analysis (Storey et al, 1964), can properly take into consideration the land treatment location. They therefore inadequately account for the effects of catchment storage. A more satisfactory prediction method would be one which actually simulates the catchment storage effect. Numerous models have been developed to do this in either physical or mathematical form. A description of such models appears in Chapter 3. They all require a land-use parameter which is altered to simulate land-use changes. Often a lack of information prevents the quantitative expression of changes in land use by such a parameter. In these cases the sensitivity analysis technique described below appeals as a satisfactory alternative.

1.4 SENSITIVITY ANALYSIS TECHNIQUE

The sensitivity analysis technique, of the type proposed by Burton (1969), is a method for evaluating the hydrological sensitivity of different parts of a catchment to land-use changes. It uses a model whose structure is based on the sub-areas of a catchment and incorporates parameters that are meaningful and measurable land-use indices for the sub-areas.

Assume that afforestation in a certain sub-area of a catchment is proposed as a means of reducing the flood peak at the catchment outlet. If, in the model, an unrealistically large change in the land-use index for that sub-area is necessary to reduce the flood peak according to some design criterion, then the sub-area is hydrologically insensitive to afforestation. The afforestation proposal can then be rejected.

The advantage of this technique is that no specific numerical values are required to determine the sensitivity of the various sub-areas. If the sub-area under investigation is found to be sensitive to changes in the land-use index, then an examination of the values of the changes is necessary. Detailed information about the change in land-use index following the proposed treatment is then required.

1.5 THE PRESENT INVESTIGATION

A method was sought which could be used for any catchment to predict the effects of land-use changes on the flood peak and the quantity of suspended sediment transported in a flood. It was essential that the method simulated the catchment storage effect and incorporated the sensitivity analysis technique. Obtaining a relationship between the method's land-use index and different land uses was a desirable but less important objective.

With afforestation being the most popular form of land treatment in large catchments in New Zealand it was taken as the principal form of land-use change in this study.

Some hydrological effects of changes in forest cover are reviewed in Chapter 2. In Chapter 3 a model suited to this investigation (the Laurenson model) is described and its application to the Motueka catchment is outlined in Chapter 4. The analytical aspects of the investigation, including data preparation, are given in Chapter 5. The results, presented in Chapter 6, are evaluated in Chapter 7 and the investigation is summarised in Chapter 8.

CHAPTER 2

SOME HYDROLOGICAL EFFECTS OF CHANGES IN FOREST COVER

The effects of forests on floods and suspended sediment are reviewed in Sections 2.1 and 2.2, respectively. The effects are then summarised in Section 2.3.

2.1 FORESTS AND FLOODS

2.1.1 Increase in Forest Cover

Forests promote infiltration, i.e. the entry of water into the soil through the ground surface. They achieve this in the following ways.

(a) The root system maintains a relatively stable and porous soil structure.

(b) The litter cover and the leaf mould protect the soil from compaction by raindrops.

(c) The litter cover also retards any overland flow and hinders the surface sealing of soil pores.

(d) Evapotranspiration, which depends on the climate and the depth of the root zone, causes soil moisture deficiencies and so increases the potential for infiltration.

Lull and Reinhart (1972) report that in mature forest infiltration is seldom limiting: infiltration rates generally exceed rainfall intensities so that overland flow is virtually absent. They also point out that the surface runoff (defined in Section 5.1.1) from a forested catchment is due almost entirely to subsurface flow. The infiltrating water moves rapidly to the stream channels through the large voids in the topsoil which have been formed by the forest root system.

The net result of forests promoting infiltration and providing greater opportunity for soil moisture storage is a reduction in surface runoff. Consequently, flood peak discharges are also reduced. According to Lull (1971), afforestation of eroding land can reduce peak discharges by up to 60 to 90 percent.

However, the reduction in peak discharge with increase in forest cover has been found to be extremely variable and is dependent on many factors. The reduction depends on the proportion of a catchment forested (Lull and Reinhart, 1972). It also depends on the climate and the season, since these factors affect evapotranspiration and thus the opportunity for soil moisture storage. For instance, in winter the opportunity for infiltrating water to be stored or detained in the soil is less than that in the summer, when evapotranspiration is greater and the soil moisture deficit is correspondingly higher. Hence, peak discharge reductions are usually higher in summer than in winter. In the White Hollow catchment, a Tennessee Valley Authority (TVA) catchment of 1715 acres (6.94 km^2), improvement in forest cover over a 24 year period reduced summer peak discharges by about 80 percent (Ellersten, 1968). The reductions for the winter storms were much less, ranging from 0 to 28 percent.

Further, the reduction in peak discharge depends on the magnitude of the storm. In the large storm the proportion of the infiltrating water stored or detained in the soil will normally be less than that for the small storm. Thus the peak discharge reduction will generally be less significant in the large storm (Kittredge, 1948; Leopold, 1970).

Nevertheless, the reduction in peak discharge in a large storm can be substantial. Pereira (1973) reports of a large storm in Kenya on land already wet from ten days of rainfall. Over three inches (76 mm) of rain fell in one hour during the storm, and the peak rainfall intensity was approximately 10 in/hr (250 mm/hr). Despite these extreme rainfall conditions, the peak discharge per unit area for a cleared and cultivated catchment was more than forty times greater than that for a nearby, forested catchment.

The depth of soil is another factor that affects the reduction in peak discharge. With shallow soils over impermeable rock the initial infiltration rate is still high, but rapid saturation of the soil occurs. Thus the forest on a shallow soil can delay the onset of surface runoff, but its control over surface runoff and the peak discharge diminishes in a prolonged storm where the foliage, litter cover and the soil all become saturated. For example, in a low-intensity storm in the Appalachian mountains where 8 inches (203 mm) of rain fell on wet, forested catchments, the peak discharge per unit area for a catchment with only a 2 foot (0.6 m) depth of soil was more than five times that for a catchment where the soil was 6 feet (1.8 m) deep (Hursh, 1943).

In addition to the factors already mentioned, the reduction in peak discharge depends on the catchment storage and the location of the forest cover increase, for the reasons given in Section 1.2. These two factors have not always been properly accounted for in research, and the latter one especially has not been closely examined. Lull and Reinhart (1972) have noted, though, a tendency for the forest influence in reducing the flood peak to diminish with increasing catchment size.

Forest influences on the streamflow are not confined to the tropical and temperate climatic zones. Extensive observations have been made of the forest influences in the northeastern area of European USSR. In this area most of the precipitation occurs as snow and the major runoff events each year are due to snowmelt. For these conditions it has also been observed that forests transform the runoff pattern. From a summary of a century of Russian observations and opinions, Molchanov (1963) concluded that when a catchment is selectively forested, to 30-40 percent of its area, all overland flow is transferred to the subsoil. Sokolovsky (1959) indicated that the reductions in overland flow and the subsequent recharge of groundwater caused low flows to increase three to five times.

The reductions in overland flow are again the result of forests improving the conditions for infiltration. Forests lessen the freezing of the soil, and also provide a longer time for infiltration by delaying and attenuating the snowmelt.

This latter effect is due to the forest intercepting radiation and desynchronising the snowmelt in different parts of a catchment. Sozykin (1959) noted that the melting of snow takes approximately twice as long in forests as it does in open areas, while Goodell (1959) found that snow in unshaded forest openings melts 20 to 30 percent faster than snow shaded by forest.

Boughton (1970) concluded that, because of the delay and attentuation effect on snowmelt, forests can significantly reduce peak flows in large catchments where snowmelt is the principal flood-producing factor.

The effect has also led to consideration of the optimum forested area for a catchment in a snow region. Ivanov (1951) determined that the most beneficial effect of forests in limiting the release of waters in times of flood is when approximately 50 percent of the catchment is in forest.

2.1.2 Decrease in Forest Cover

When the forest cover in a catchment is reduced the effects are the converse of those produced by afforestation, i.e. surface runoff and peak discharges are increased (e.g. Nakano, 1967). Further, because the difference in soil moisture deficits between forested and deforested catchments is generally greater in summer, the increases are usually higher in the summer. In a deforestation experiment on a 39.5 acre (0.16 km^2) catchment in New Hampshire, USA, Hornbeck (1973) observed that by far the greatest increases in direct runoff (surface runoff plus interflow) and peak flows occurred during the summer season. Over the period of the experiment the greatest increases in direct runoff and peak discharge, of two and threefold respectively, occurred in a summer storm when there was a large soil moisture deficit in the forested control catchment.

The method of removing the forest cover affects the streamflow increases. Provided the A_0 and A_1 horizons of the soil are well developed and essentially undisturbed after forest removal, the increases can be minimal (Kittredge, 1948). For example, with forest cutting alone, the remaining vegetation may sometimes be as effective as the uncut forest in minimising surface runoff and peak discharges (e.g. Hewlett and Hibbert, 1961).

In comparison, logging and fire are much more drastic forms of deforestation. Both forms disturb the soil surface, reduce the soil porosity and expose the surface to compaction by raindrops. The resultant decrease in infiltration can produce substantial streamflow increases. Following a severe forest fire in a steep, Australian catchment, the peak discharge was in the order of twenty eight times greater than that for a similar storm prior to the fire (Brown, 1972).

Reforestation of a deforested catchment rapidly reduces the surface runoff and peak discharges (Leopold, 1970). In the White Hollow catchment (see Section 2.1.1) the peak discharge reductions of about 80 percent were achieved within the first two or three years after the reforestation. Further, the results (Hibbert, 1967) of water yield studies at Coweeta, North Carolina, give an indication that after reforestation the streamflow variables return almost to their original values.

2.2 FORESTS AND SUSPENDED SEDIMENT

Afforestation of eroding land sharply curbs erosion and reduces the quantity of suspended sediment. For example, with land in Mississippi where erosion had removed the equivalent depth of two feet (0.6 m) of soil, afforestation reduced the annual soil loss rate from several tons/acre to 0.00-0.08 tons/acre (Ursic and Dendy, 1965). And in two TVA catchments, the White Hollow catchment and the 88 acre (0.35 km^2) Pine Tree Branch catchment, improved forest cover on eroding land contributed to a lowering in the annual sediment load of 96 and 98 percent, respectively (Ellersten, 1968).

Afforestation reduces the quantity of suspended sediment through the following mechanisms:

(a) by decreasing overland flow and surface runoff (Section 2.1.1), and therefore the sediment transporting capacity;

(b) by protecting the soil against raindrop action, by decreasing the detaching energy of the raindrops and the detachability of the soil particles (Osborn, 1955);

(c) by protecting the soil against erosion by wind;

(d) by stabilising the soil surface; and

(e) by increasing the deep-seated land stability, by the mechanical reinforcement from the root system and by the alteration of the soil moisture regime.

The decrease in overland flow (mechanism a) reduces the number of particles transported to the river system, while the decrease in surface runoff (also mechanism a) reduces the quantity of sediment transported by the river itself. Since the sediment transporting capacity of a river increases at the rate of the second or third power of its velocity a decrease in surface runoff, which is usually accompanied by decreased river velocities, may reduce the sediment load considerably. The reduction is magnified by the remaining four mechanisms, which restrict the source and supply of sediment.

Because forests reduce surface runoff and the quantity of suspended sediment they act as a control on floods. They decrease peak discharges and also decelerate the downstream riverbed aggradation.

Forests also maintain a high water quality. The water from catchments in well-established forest characteristically contains very low suspended sediment amounts, except in times of infrequent high flows (Packer, 1967; Lull and Reinhart, 1972).

However, removal of the forest cover reverses the mechanisms listed earlier and noticeably increases the quantity of suspended sediment. As with streamflow, the most dramatic increases follow deforestation by logging and fire. Depending on the degree of soil compaction and disturbance, these increases may be in the order of one thousand times greater than the original values (Reinhart et al, 1963; Unesco, 1972).

2.3 SUMMARY

Outstanding characteristics of forests are their promotion of infiltration, their increasing of the soil moisture storage capacity, and their physical effect in stabilising the soil. As a consequence of the first two characteristics, afforestation reduces overland flow, surface runoff and peak discharges. The combination of the three characteristics causes a marked decline in the quantity of suspended sediment. With deforestation, the reverse effects occur.

Although these effects of changes in forest cover are qualitatively consistent, quantitatively they are highly variable and are therefore difficult to predict. For instance, the reduction in peak discharge following afforestation varies according to the extent of the treatment, the climate, the season, the storm and the soil conditions. In a prediction these factors can be handled satisfactorily by a multiple regression equation. What cannot be handled so easily is the fact that the reduction in peak discharge also depends on the catchment storage and the treatment location - two factors which have not always been given due recognition in research.

The reduction in the suspended sediment quantity following afforestation is also dependent on these two factors, since the quantity is influenced by the river discharge as well as by the soil stability.

Because this investigation was concerned with the development of a method for predicting the effects of land treatment on peak discharge and the quantity of suspended sediment transported in a flood, emphasis was placed on accounting for these factors of catchment storage and the treatment location. Although the principal form of land treatment in this study was afforestation, the problems posed by catchment storage and the treatment location are the same whatever the form of land treatment.

Simulation was considered the most satisfactory way of accounting for the two factors. The model that was used in the simulation is described in Chapter 3.

CHAPTER 3

SELECTION OF A MODEL

The Laurenson model was selected for use in this investigation and it is described in Section 3.4. The description is preceded by a list of the selection criteria (Section 3.1), a general classification of relevant prediction models (Section 3.2) and comments on individual models (Section 3.3). In the last section (3.5) the Laurenson model's loss rate parameter is explained and then justified as a suitable land-use index for a sensitivity analysis.

3.1 OBJECTIVE AND REQUIREMENTS OF THE MODEL

A prerequisite for an accurate prediction of land treatment effects on the flood peak and the quantity of suspended sediment transported in a flood is a satisfactory reproduction of the flood hydrograph. With this as the chosen objective of the model sought, it was important that the model should have the following attributes.

(a) Applicability to hydrologically small and large catchments alike, i.e. the catchment storage effect should be simulated.

(b) Structural facility for a sensitivity analysis, i.e. the model should contain sub-areas.

(c) A physically meaningful and measurable parameter that would serve as the land-use index in the sensitivity analysis.

(d) Minimal input data to ensure the model's wide use.

3.2 A CLASSIFICATION OF MODELS

Models that can be applied to predict the hydrological effects of land treatment can be classified according to an adaptation of Chow's (1972) system (see Figure 3.1).

The physical models resemble or imitate the major hydrological processes within the catchment. Their division into scale, analogue and simulation models, respectively, depends on whether:

(a) the model is a reduced physical replica;

(b) the behaviour of the model's components are analogous, in a mathematical sense, to the hydrological processes; or

(c) the model is in digital form.

With the abstract model there is no attempt to model the hydrological processes exactly. Instead the processes are replaced by a set of mathematical relationships that approximate the catchment's runoff behaviour.

The lumped form of abstract model may be linear or non-linear. It treats the catchment as a single point in space without dimensions and assumes homogeneity of the input data and homogeneous catchment conditions. On the other hand, the distributed model considers the runoff behaviour within the catchment, so that its mathematical formulation contains space dimensions.

A special case of the lumped model is the conglomerated lumped model. In this model the internal space of the catchment comprises a number of unit spaces, and each unit space is treated as a lumped sub-catchment model.

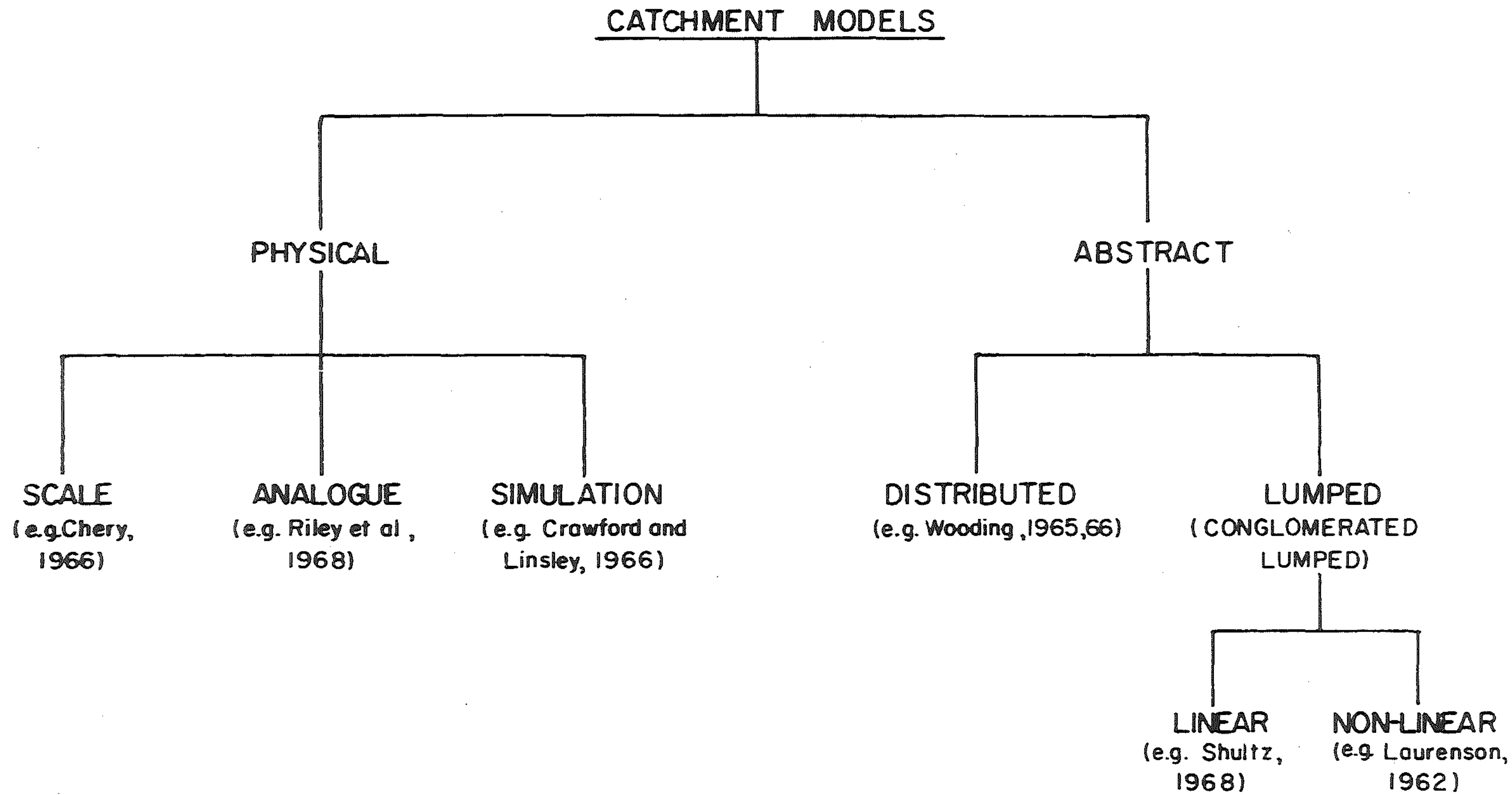


FIG. 3.1: A CLASSIFICATION OF PREDICTION MODELS — Adapted from Chow (1972)

3.3 WHICH MODEL?

3.3.1 General

The criteria for selecting a model were the objective and requirements in Section 3.1.

Neither analogue nor physical models were seriously considered because both lack generality. Moreover, physical models require extensive field data and are susceptible to similarity problems.

The different models that were considered are mentioned below.

3.3.2 Simulation Models

The Stanford Watershed model (Crawford and Linsley, 1966) simulates the basic processes of the land phase of the hydrological cycle. It has been used to study effects of land-use changes (e.g. Fleming, 1971) but was inappropriate in this present situation because of:

(a) the extensive data demands for each sub-area - information on over twenty parameters is required;

(b) the natural tendency, as a consequence of point (a), to use a minimal number of sub-areas;

(c) the uncertainty over a suitable land-use index.

Point (c) arises from the need to estimate values for some parameters e.g. the infiltration parameter. The estimation is usually performed by optimising the parameter values, i.e. the values are repeatedly adjusted by trial and error until the best-fit reproduction is attained. Although the results by this method are frequently impressive, the fitted or so-called optimum parameter values can bear little resemblance to actual catchment values.

This was a finding with the Dawdy and O'Donnell (1965) model. The model is a water balance approach like the Stanford model, but less sophisticated, and it was designed primarily to test optimisation techniques. Because of the ease with which parameter values could be fitted, the techniques were seen to permit refinements of a model by encouraging the addition of more parameters. It was concluded, however, that while refinements may improve a model's performance the optimum parameter values may reflect reality less and less. The same warning on the potential abuse of optimisation techniques was reiterated by Kane et al (1973).

While containing fewer components than the Stanford model, the Boughton (1965, 1968a) model is proving a useful tool in water yield problems, and improvements by Jones (1969) and Taylor (1971) have enhanced its reputation in this field. The model works on daily surface runoff volumes, though it was modified later (Chapman, 1968, 1970) to operate on shorter time intervals.

Another prominent simulation model is the USDAHL-70 model (Holtan and Lopez, 1971), and it has been applied to evaluate effects of land-use changes, e.g. Glymph et al (1971). The model differs from those previously mentioned in that no optimisation technique is used. The output is computed from predetermined, specific values for the different parameters. This requires extensive field data.

3.3.3 Distributed Models

Wooding's (1965, 1966) model applies kinematic wave theory to describe both overland flow and streamflow in a catchment. A plane, V-shaped catchment is assumed and overland flow is taken to occur over the rectangular planes to the stream channel, assumed along the apex of the V.

Despite improvements by Woolhiser, in association with others (Woolhiser et al , 1970; Kibler and Woolhiser, 1970; Smith and Woolhiser, 1971), the Wooding-type model appears limited in its use by its emphasis on overland flow, which is not the major factor influencing the streamflow of a large, rural catchment.

3.3.4 Conglomerated Lumped Models

3.3.4.1 Catchment Storage

In a conglomerated lumped model the rainfall excess is routed, according to a concept of the runoff process, through a representation of catchment storage that involves sub-areas. The catchment storage can be represented by concentrated and distributed storages. The two types of storage are differentiated by their dominant effect on a hydrograph. Although both types attenuate and translate a hydrograph, the former effect is principally associated with a concentrated storage (e.g. a reservoir) and the latter with a distributed storage (e.g. a channel).

Laurenson (1962) showed the futility of separating the effects of the two types of storage in a model. A series of concentrated storages was found to simulate both the attenuation and translation effects.

3.3.4.2 Non-Linear Models

Catchment streamflow exhibits a non-linear response to rainfall input. This was shown in studies by Singh (1962), Diskin (1964), Kulandaiswamy (1964) and Askew (1968a). While it is often debatable whether the non-linearity of a catchment is sufficiently pronounced to warrant non-linear considerations, only the non-linear models were considered.

In his model of the Columbia Basin Rockwood (1958) used non-linear reservoirs to represent lake, channel and catchment storages. The combination of reservoirs resembled the hydrological structure of the Basin.

The Laurenson (1962) model, shown in two idealised forms in Figure 3.2, has greater flexibility and simulates the response of a catchment as a whole, rather than distinguishing between the responses of the land and channel components. The model considers sub-areas of a catchment and a non-linear reservoir at the centre/centroid of each. The rainfall excess for each sub-area is assumed spatially uniform and concentrated at the location of the reservoir.

The rainfall excess for a sub-area is converted to an equivalent hydrograph, combined with the routed outflow from the adjacent, upstream reservoir(s), and then routed through the reservoir in the sub-area concerned. Repetition of this process down to the catchment outlet produces the surface runoff hydrograph. In operating in this manner the Laurenson model allows for:

(a) spatial (between sub-areas) and temporal variations in rainfall excess;
(b) rainfall excesses from different parts of the catchment passing through different amounts of catchment storage,
(c) catchment storage being distributed rather than concentrated;
(d) non-linear catchment behaviour, i.e. the non-linear relationship between catchment storage and streamflow discharge.

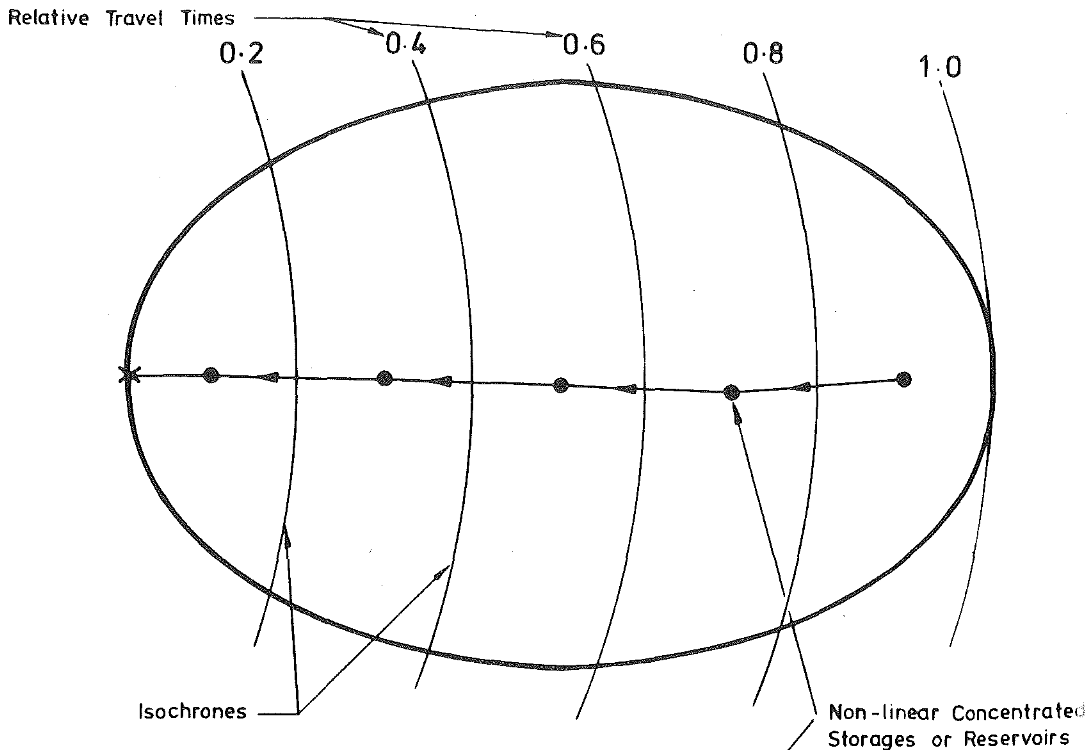


FIG. 3.2a ISOCHRONAL SUB-AREA APPROACH

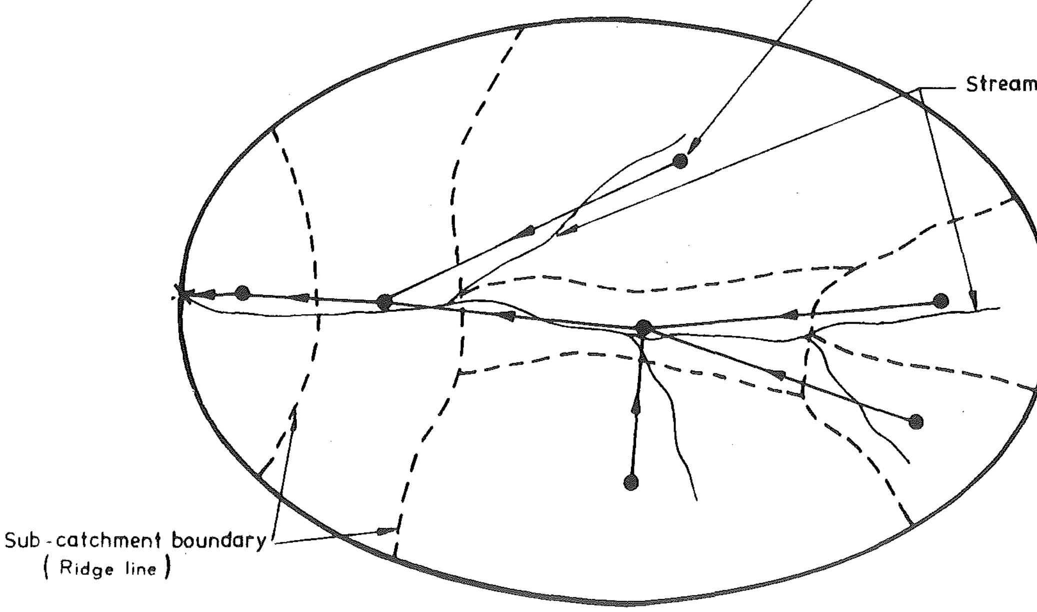


FIG. 3.2b SUB-CATCHMENT SUB-AREA APPROACH

FIG. 3.2 : TWO IDEALISED FORMS OF THE LAURENSON MODEL

For these reasons it was decided to use the Laurenson model. A fuller description of the model follows.

3.4 THE LAURENSON MODEL

3.4.1 Structure

The Laurenson model requires the catchment to be divided into sub-areas, each containing a non-linear reservoir. The division into sub-areas can be done in any reasonable way. In the most common form of the model, the isochronal approach (Figure 3.2a), the sub-areas are defined by isochrones, i.e. lines of equal relative travel time (see Section 3.4.2), and the reservoirs are located at the sub-area centres, i.e. halfway between the isochrones.

In a second and less promoted form of the Laurenson model, the sub-catchment approach (Figure 3.2b), the sub-areas are defined by sub-catchment boundaries and the reservoirs are located at the centroids of the sub-areas. This modelling approach achieves a closer approximation of the drainage system. The advantages of the sub-catchment approach are:

(a) the time spent in constructing the model is much less; and

(b) the sub-division of the model is more adaptable and meaningful for land treatment problems than the imaginary isochronal sub-areas.

The sub-catchment approach is virtually untested; in its sole trial by Laurenson (1962) it performed less creditably than the isochronal approach. On the basis of its practical advantages alone it was considered worthy of further research.

3.4.2 Travel Time

To be able to route surface runoff through the Laurenson model it is required to know the travel time of flow from each reservoir to the catchment outlet, as explained later in Section 3.4.4. Laurenson rejected the drop-of-water concept in considering travel time. He treated the travel time for a point in the catchment as the time between the occurrence of an element of rainfall excess at the point and the effect of this element at the outlet. The complication in treating travel times in this more realistic fashion is that the times then depend on the discharge. It is therefore convenient to obtain the travel times for the reservoirs initiall in dimensionless form, expressing them in relation to the maximum travel time for a point in the catchment. The relative travel times can later be made dimensional when the travel time is determined for a point in the catchment with which other points can be associated.

Relative travel times for points in a catchment are calculated on the premise that the travel time of flow from a point along the point's flow path to the outlet is proportion to $\Sigma l/S^{\frac{1}{2}}$; where l is the length of flow path between a pair of adjacent contours, S is the slope of the corresponding reach, and the summation is performed along the flow path from the point to the outlet. Travel times calculated in this way are then made relative to the maximum time calculated for the catchment.

In the isochronal approach the relative travel times for the reservoirs are obtained by determining dimensionless isochrones (see Figure 3.2a) and then placing the reservoirs halfway between the isochrones. In order to obtain the isochrones relative travel times must be calculated for a large number (200-600) of points in the catchment.

In the sub-catchment approach the obtaining of the relative travel times for the reservoirs is much less demanding. Isochrones are not needed to locate the reservoirs, so that it is only necessary to calculate the relative travel times for the reservoir location points.

3.4.3 Catchment Lag

Catchment lag provides the link between travel time and discharge. It is defined as the difference in time between the centroids of the catchment rainfall excess and the resulting surface runoff hydrograph. In effect, catchment lag is the average travel time for all points in the catchment, where the averaging is done throughout the duration of the storm.

Laurenson showed that, for a small increment of time and for spatially uniform rainfall excess, the average travel time L_t was equal to the abscissa of the centroid of the dimensional~~ess~~ time-area diagram. Thus the travel time τ for a point may be expressed as

$$\tau = \frac{\tau_R}{Y} L_t \qquad \text{.......... 3.1}$$

where τ_R = the corresponding relative travel time;

and Y = the abscissa value of the centroid of the dimensionless time-area diagram.

In fact the time-area diagram is not required to obtain Y; Y can be calculated from

$$Y = \frac{\sum_{i=1}^{ns} A_s \tau_R}{\sum_{i=1}^{ns} A_s} \qquad \text{.......... 3.2}$$

where A_s = area of a sub-area

τ_R = the relative travel time for the reservoir in the sub-area;

and ns = the number of sub-areas in the catchment.

To explain how L_t in Equation 3.1 varied with discharge Laurenson examined the behaviour of the time-average value of L_t, the catchment lag L. From an analysis of twenty three storms he established the following relationship for the 35 square mile (90 km^2) South Creek catchment in New South Wales.

$$L = 64\bar{q}_T^{-0.27} \qquad \text{.......... 3.3}$$

where L = catchment lag, in hours;

and $\bar{q}_T$ = mean rate of total runoff over the period of surface runoff, in cusecs.

In a similar but more detailed study, Askew (1968a,b) found that the correlation between the two variables improved if a weighted mean discharge $\bar{q}_{TD}$ was considered, where

$$\bar{q}_{TD} = \frac{\sum_{i=1}^{n} q_T\, q_D}{\sum_{i=1}^{n} q_D} \qquad \text{.......... 3.4}$$

where $\bar{q}_{TD}$ = weighted mean rate of total runoff over the period of direct runoff (surface runoff plus interflow);

q_D = a regularly spaced ordinate of direct runoff;

q_T = the corresponding ordinate of total runoff;

and n = the number of ordinates of direct runoff.

By relating catchment lag to topographical variables as well as $\bar{q}_{TD}$, and using data on five rural catchments (including South Creek) in New South Wales with areas ranging from 0.15-35 square miles (0.39-90 km^2), Askew developed three equations, one of which was

$$L = 5.64A_c^{0.541}S_s^{-0.16}\bar{q}_{TD}^{-0.23} \qquad \ldots\ldots\ldots\ldots 3.5$$

where $\bar{q}_{TD}$ is in cusecs, A_c is the catchment area in square miles and S_s is a dimensionless overland slope factor. S_s is determined by overlaying a square grid of lines onto a contour map of the catchment and applying the formula

$$S_s = \frac{Nh}{L_g} \qquad \ldots\ldots\ldots\ldots 3.6$$

where N = the number of intersections of grid lines with contours;

h = the contour interval;

and L_g = the total length of the grid lines within the catchment.

It will be noted that the general form of the lag-mean discharge relationships derived by Laurenson and Askew is

$$L = A\bar{q}^{-B} \qquad \ldots\ldots\ldots\ldots 3.7$$

where $\bar{q}$ is some form of mean discharge and A and B are positive constants.

Although A and B in Equation 3.7 relate to time-average values of lag and discharge, Laurenson assumed that they could also be applied to the instantaneous values of the two variables. Hence

$$L_t = Aq^{-B} \qquad \ldots\ldots\ldots\ldots 3.8$$

where q is an instantaneous rate of runoff.

Substitution for L_t in Equation 3.1 using Equation 3.8 produced the general equation of the travel time τ for any point in the catchment, namely

$$\tau = \frac{\tau_R}{Y} Aq^{-B} \qquad \text{.......... 3.9}$$

3.4.4 Routing

Inflow to each reservoir in the Laurenson model is routed according to the non-linear storage function

$$S = K(q).q \qquad \text{.......... 3.10}$$

where S = a volume of storage;

and K = the delay time of flow through the reservoir - it is a function of the outflow discharge q from the reservoir.

The delay time K through a reservoir accounts for the travel time of the flow in the model flow reach between the reservoir and the next one downstream. It is equal to the difference in the travel time for the two reservoirs. Thus, from Equation 3.9,

$$K = \frac{\Delta\tau_R}{Y} Aq^{-B} \qquad \text{.......... 3.11}$$

where $\Delta\tau_R$ = the difference in the relative travel time for the two reservoirs

The routing procedure itself involves the iterative solution, for each routing period, of the following Muskingum-type equation, which is obtained from storage continuity considerations and Equation 3.10.

$$q_2 = ai_2 + bi_1 + cq_1 \qquad \text{.......... 3.12}$$

where subscripts 1 and 2 refer, respectively, to the start and end of the routing period, of duration Δt, and where

q = an instantaneous rate of outflow from the reservoir;

i = an instantaneous rate of inflow to the reservoir;

$$a = b = \frac{\Delta t}{2K_2 + \Delta t} \qquad \text{.......... 3.13}$$

$$c = \frac{2K_1 - \Delta t}{2K_2 + \Delta t} \qquad \text{.......... 3.14}$$

$$K_1 = \frac{\Delta \tau_R}{Y} Aq_1^{-B} \qquad \text{.......... 3.15}$$

and $$K_2 = \frac{\Delta \tau_R}{Y} Aq_2^{-B} \qquad \text{.......... 3.16}$$

Equations 3.15 and 3.16 are discrete forms of the general reservoir delay time-discharge relationship (Eq. 3.11). It can be observed from these equations that the lag or delay time characteristics of each reservoir are like those of the catchment as a whole, i.e. each reservoir's delay time depends on the constants A and B. This assumption appears reasonable for catchments of small or moderate size. However, in a large catchment with marked spatial variations in topography it would be more realistic to divide the catchment into smaller ones, according to the available gauging stations,and model each smaller catchment separately. The overall model would then consist of a number of separate models.

The assumption that the same A and B values apply to each reservoir, and therefore to each sub-area, is necessary for the isochronal approach. With the sub-catchment approach, however, there is a possibility that a different set of A and B values could be obtained for each sub-area by using an equation like Askew's (Eq. 3.5). This topic was not examined in this study, though it seems one worth investigating.

3.5 LOSS RATE

3.5.1 General

The rainfall excess in the Laurenson model is derived by applying a loss rate (Φ index) to the storm rainfall. The loss rate is the *average* rate at which rainfall is lost to surface runoff through being abstracted by infiltration, evapotranspiration, interception, depression and detention storage. Since these hydrological processes depend on the soil and cover characteristics (as well as the topographical and storm characteristics), the loss rate is an index of the effect of the land use on the surface runoff hydrograph. It is therefore a convenient model parameter for expressing the effects of land-use changes.

A disadvantage with the loss rate though is that its use incorrectly implies that the rate of rainfall loss remains constant throughout a storm. Some consideration was therefore given to using a more theoretically acceptable, available method of deriving the rainfall excess. However, the alternative methods available were rejected, because of their unsuitability of application or their lack of a suitable land-use index (Section 3.5.2).

3.5.2 Alternative Methods of Deriving Rainfall Excess

Methods that derive rainfall excess are based on infiltration theory. This follows since rainfall excess is that part of the rainfall that appears as surface runoff, and infiltration is the major land-based hydrological process influencing the amount and distribution of surface runoff.

The infiltration equations developed by Horton (1939), Philip (1957) and Holtan (1961) describe the infiltration capacity of a soil-cover complex as being high at the start of a storm and diminishing with time until it approaches a constant rate. The parameters in the equations may be estimated by plot experiments. However, with these experiments there are considerable practical difficulties in obtaining data representative of a large area. This is because of the variability of soil properties, both in the vertical profile and in spatial extent. Further, account has yet to be taken in these experiments of the effects of different cover on the antecedent soil moisture conditions, the factor which governs the starting point of the infiltration capacity curve. Accordingly, there is little justification for applying infiltration theory based on plot data to whole catchments. Nor is there validity in using plot data to explain effects of land-use changes in a catchment (Boughton, 1970).

Alternatively, rainfall excess can be derived by fitting an infiltration equation to the concurrent rainfall-runoff record (Musgrave and Holtan, 1964) or by optimising the equation's parameters, e.g. as in Boughton's model (Boughton, 1968b). However, the former approach is unwieldy, and is unsuited for taking spatial variations in rainfall intensity into account. With the latter approach there is the possibility of obtaining a physically meaningless parameter value.

In contrast, the loss rate approach can satisfactorily handle spatial variations in rainfall intensity (Horton, 1937; Laurenson, 1954) and the loss rate value is always a representative index of the catchment's infiltration rate. The loss rate method was therefore retained in this study to derive the rainfall excess in the Laurenson model.

3.5.3 Initial Loss

In calculating the loss rate, the early storm rainfall that only wets the catchment and produces no surface runoff is commonly classified as initial loss and excluded from the loss rate calculations. The combination of initial loss followed by a constant loss rate often approximates the infiltration capacity curve (see Figure 3.3). The approximation works best for the major flood-producing storms on a saturated catchment, and for the storms of sufficient duration and intensity such that the infiltration capacity has reached a near-constant rate early on in the storm. In the more moderate storms the loss rate is very dependent on the antecedent wetness conditions.

3.5.4 Variables Affecting the Loss Rate

Boughton (1970) suggested that loss rates may be insensitive indicators of land-use because of averaging effects in their derivation. However, the literature reviewed (Chapter 2) supported the loss rate-land use idea; the very definite manner in which afforestation promotes infiltration and reduces surface runoff indicated a noticeable increase in loss rate.

The other variables, besides land use and catchment wetness, that influence infiltration can also be expected to affect the loss rate. As indicated in Chapter 2 and mentioned by Linsley et al (1958) and/or Laurenson (1967), these variables include the soil type, the intensity and duration of the storm and the temperature.

In view of this dependency of the loss rate on many variables, any attempt to relate it with land use should also take into account the effects of the other variables.

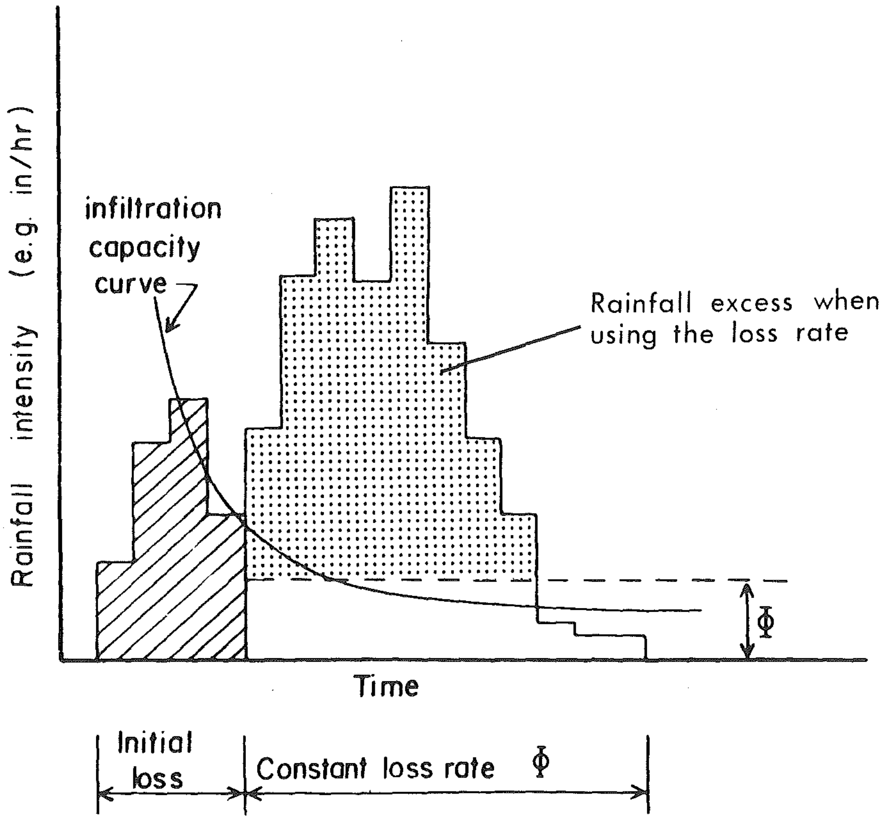


FIG. 3.3 : COMBINATION OF INITIAL LOSS AND THE LOSS RATE

CHAPTER 4

THE CATCHMENT AND ITS MODEL

The principles of the Laurenson model were applied to the Motueka catchment, producing the Motueka model. Descriptions of the catchment and its model follow in Sections 4.1 and 4.2, respectively.

4.1 THE MOTUEKA CATCHMENT

4.1.1 General Description

The 780 square mile (2020 km^2) Motueka catchment is situated at the north-west end of New Zealand's South Island (see Figure 4.1). It comprises such contrasting features as rugged, mountainous sub-catchments and flat, alluvial plains, with the relief ranging from sea level to approximately 6000 ft (1730 m). An impression of the general topography and drainage system can be gained from Map 1 (the fold-out at the end of the text) and from Figures 4.2-4.9.

Five gauging stations divide the catchment into five constituent catchments, namely the Upper Motueka, Wangapeka, Baton, Minor Woodstock and Minor Motueka catchments. The nomenclature adopted for the various parts of the catchment is summarised in Table 4.1.

Throughout this text the term true catchment refers to the total catchment area above the gauging station of the catchment concerned. A minor catchment is not a true catchment. It is the residual catchment area after the upstream constituent catchments have been deducted from the corresponding true catchment. For example, the Minor Woodstock catchment is the Woodstock catchment less the Upper Motueka, Wangapeka and Baton catchments.

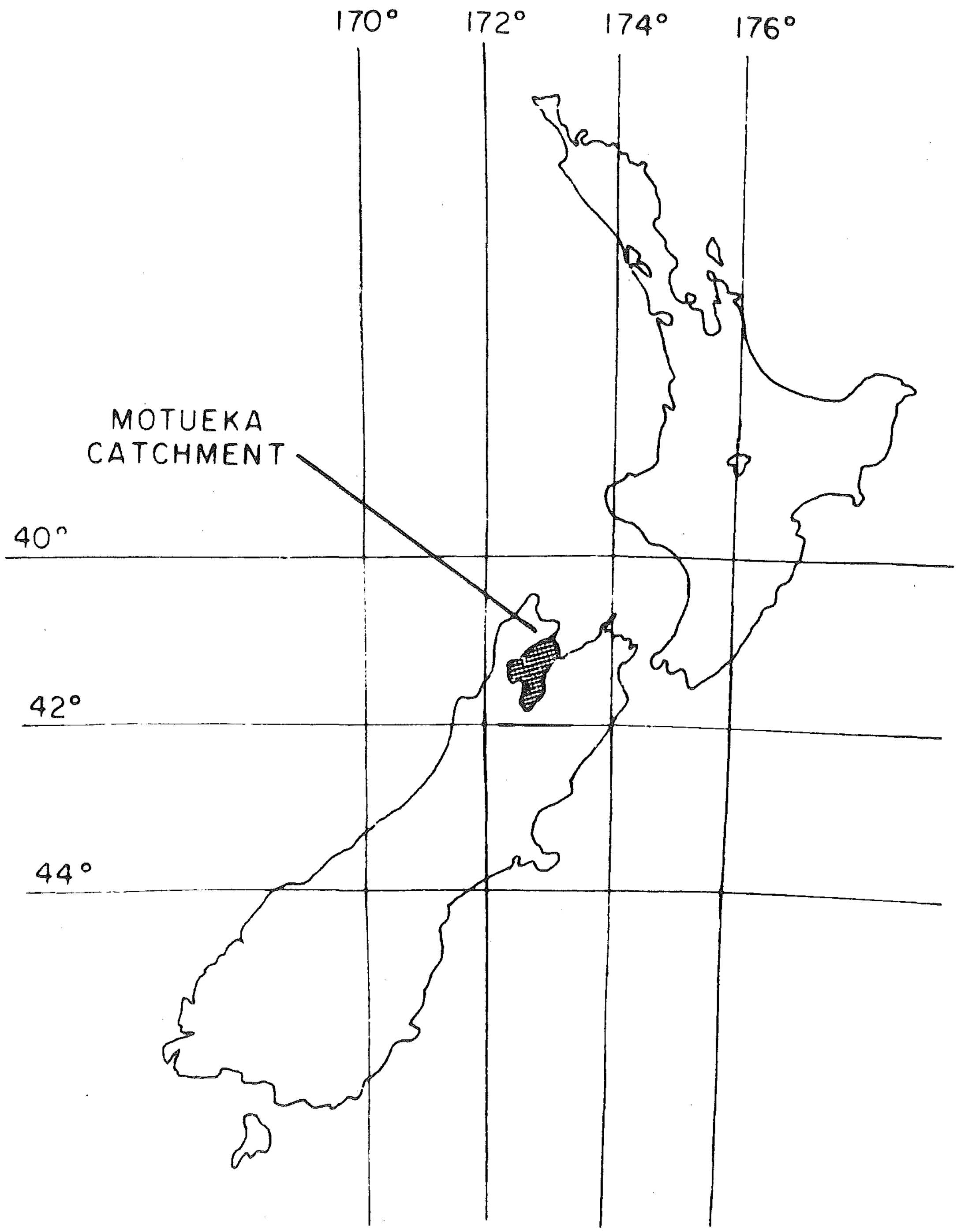


FIG. 4.1 : LOCATION OF THE MOTUEKA CATCHMENT

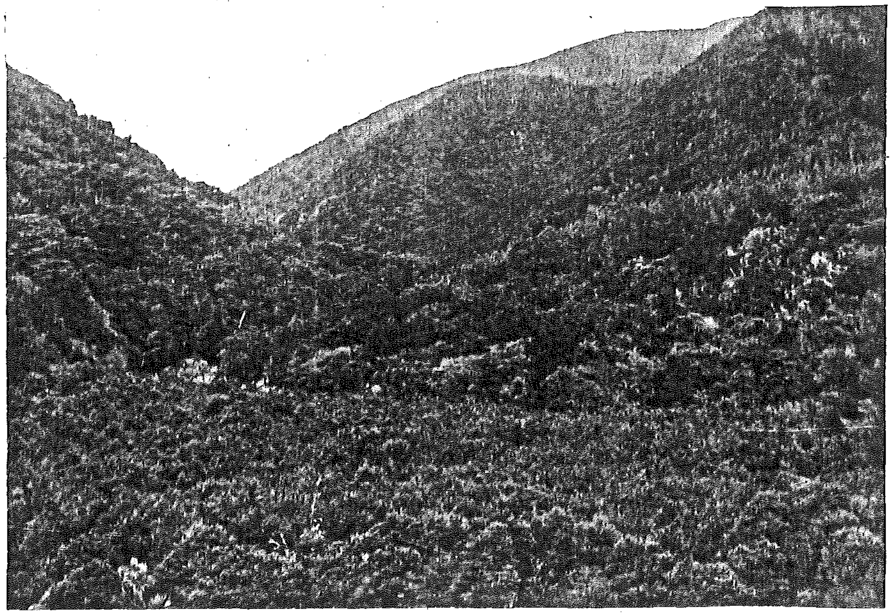


FIG. 4.2 : An upstream view from the Upper Motueka outlet

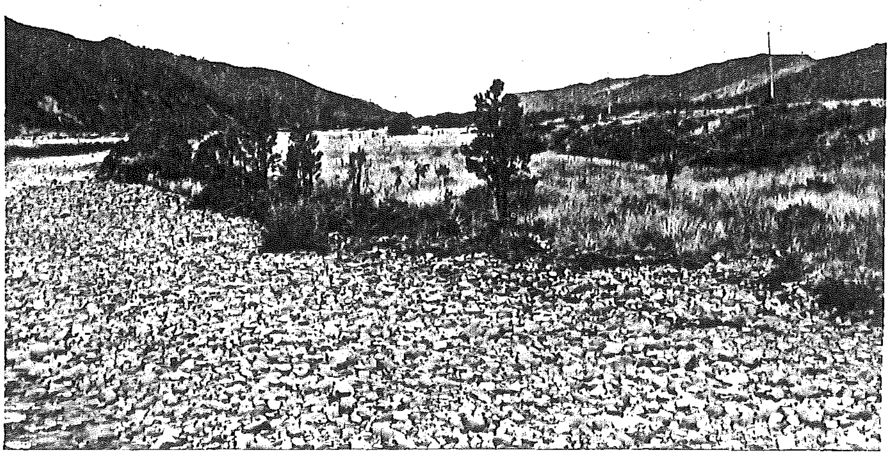


FIG. 4.3 : A downstream view from below the Upper Motueka outlet

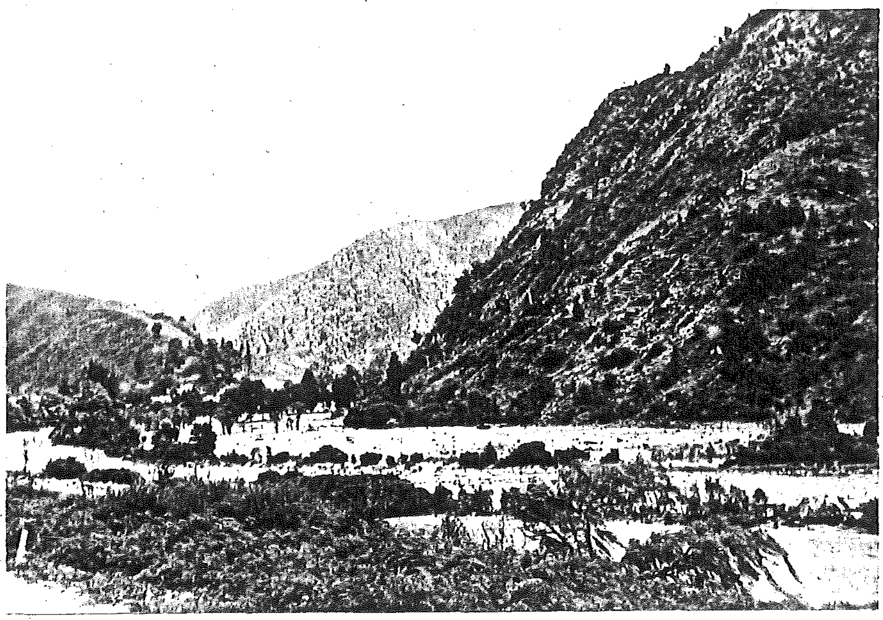


FIG. 4.4 : An upstream view from the Wangapeka outlet

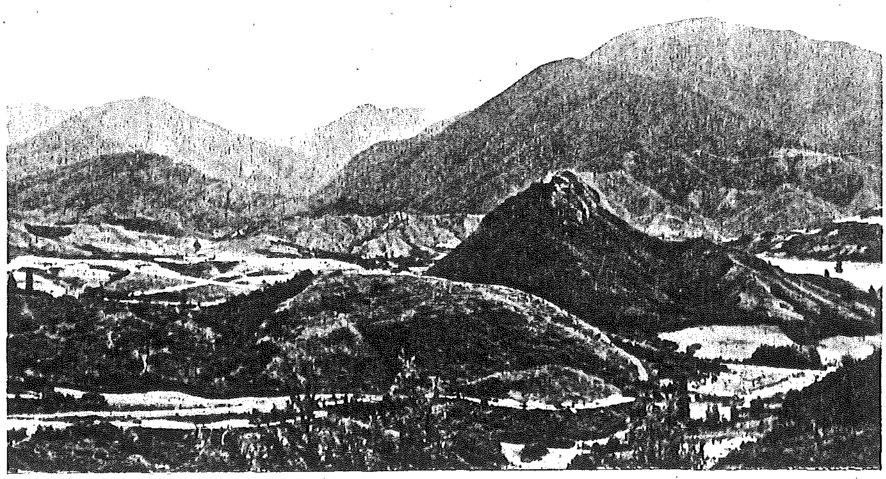


FIG. 4.5 : A westward view into the Baton catchment

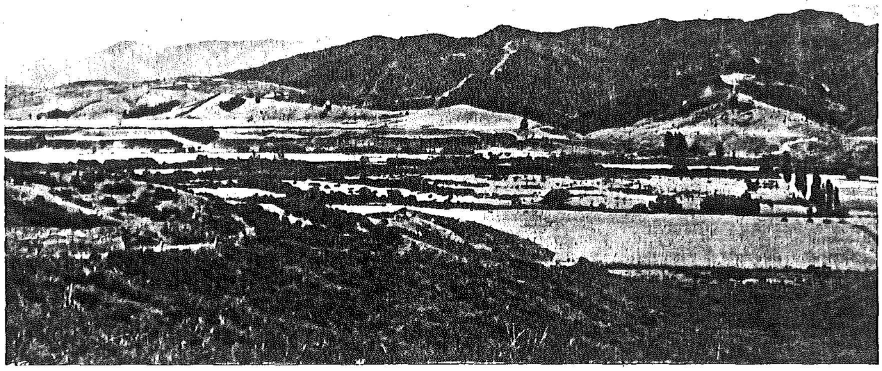


FIG. 4.6 : A westward view across the lower part of the Woodstock catchment

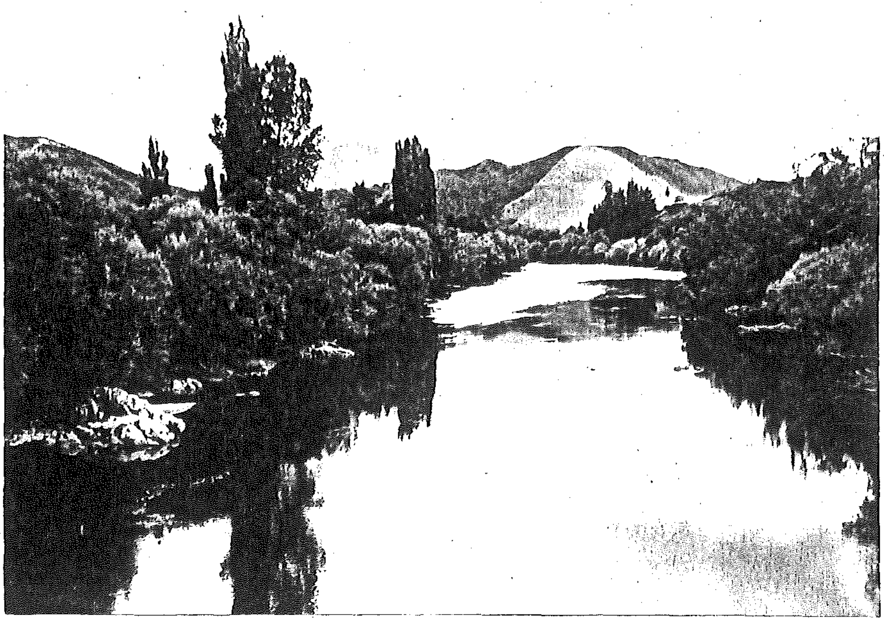


FIG. 4.7 : A downstream view from Woodstock

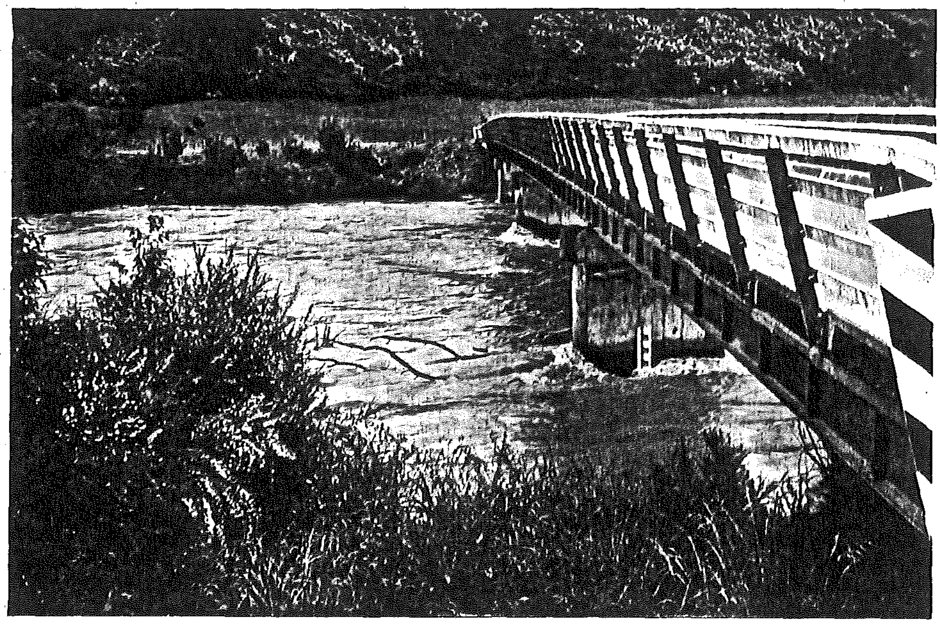


FIG. 4.8 : Flood flow at the Woodstock bridge

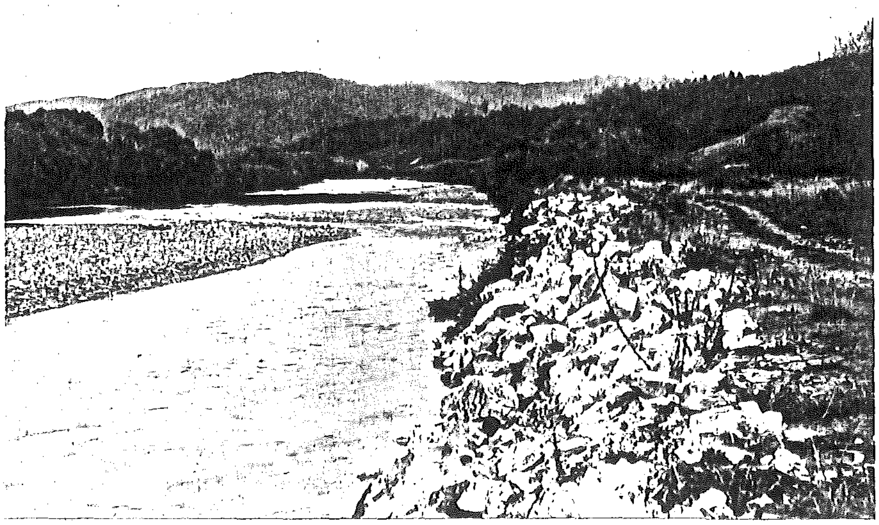


FIG. 4.9 : An upstream view towards Bluegum Corner

TABLE 4.1

CATCHMENT NOMENCLATURE AND ASSOCIATED DATA

Catchment	Gauging Station	Area		Main Channel Length		Average Channel Slope,%
		Miles^2	km^2	Miles	km	
Upper Motueka	Motueka Gorge	63.74	165.1	16.00	25.75	3.13
Wangapeka	Nettleton's	132.70	343.7	20.30	32.67	1.32
Baton	Faulkner's	68.90	178.5	10.85	17.46	3.36
Minor Woodstock	Woodstock	410.13	1062.2	-	-	-
Woodstock	Woodstock	675.47	1749.5	48.08	77.38	0.548
Minor Motueka	Bluegum Corner	104.71	271.2	-	-	-
Motueka	Bluegum Corner	780.18	2020.7	65.25	105.01	0.369

The longitudinal profiles of the main channels in the true catchments are given in Figures 4.10-4.13.

4.1.2 Climate

The Motueka catchment receives annually an average of 2300 hours of sunshine, while the average annual precipitation is approximately 55 inches (1400 mm). As the average annual isohyetal map (Figure 4.14) indicates, the greatest precipitation occurs in the western extremities of the catchment.

In summer there may be dry periods of up to a month. In winter snow accumulates at altitudes over 3000 ft (915 m) and heavy frosts (-11°C) occur inland.

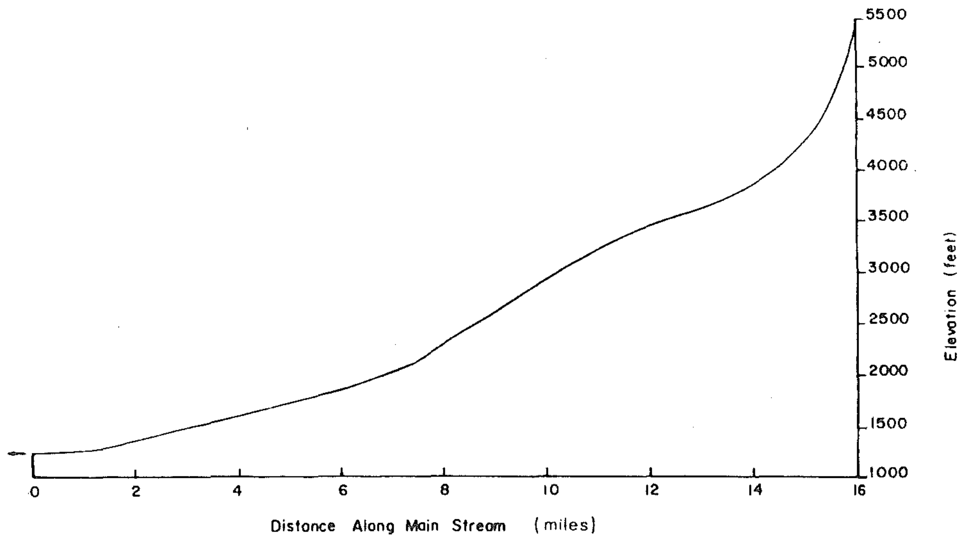


FIG. 4.10 : UPPER MOTUEKA CATCHMENT — Longitudinal Profile of Main Stream

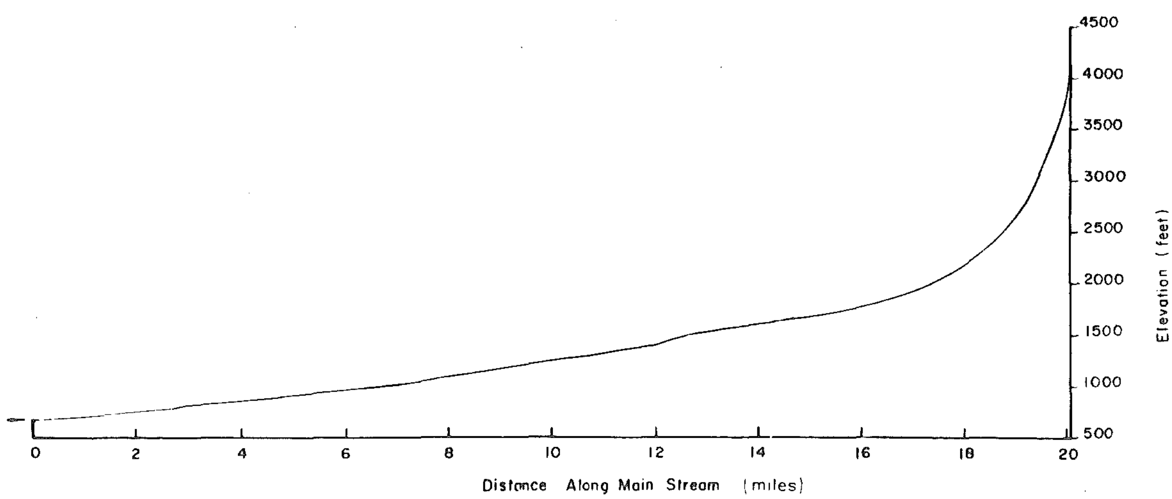


FIG. 4.11 : WANGAPEKA CATCHMENT — Longitudinal Profile of Main Stream

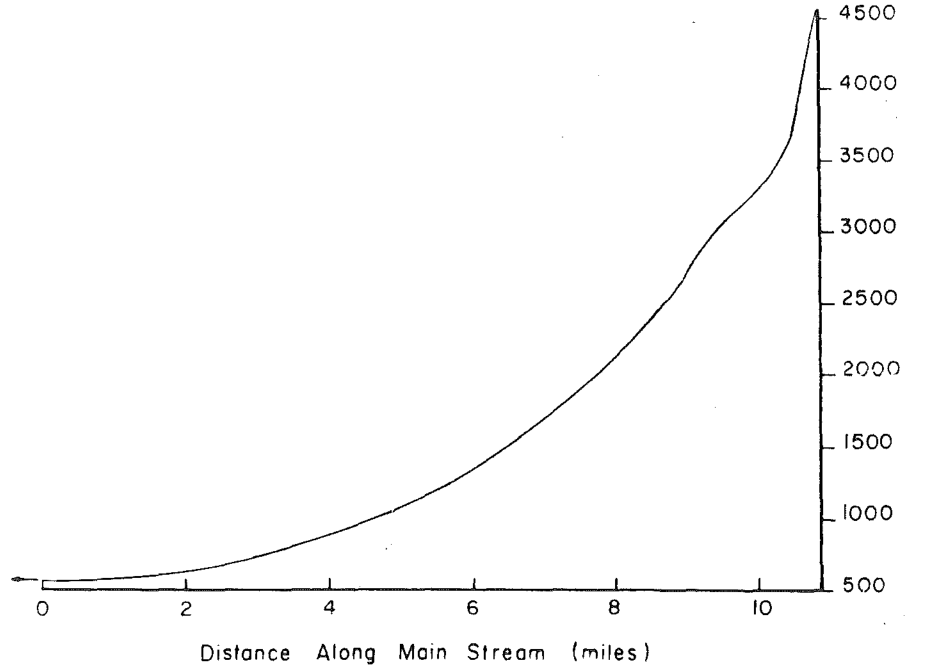


FIG. 4.12: **BATON CATCHMENT** — **Longitudinal Profile of Main Stream**

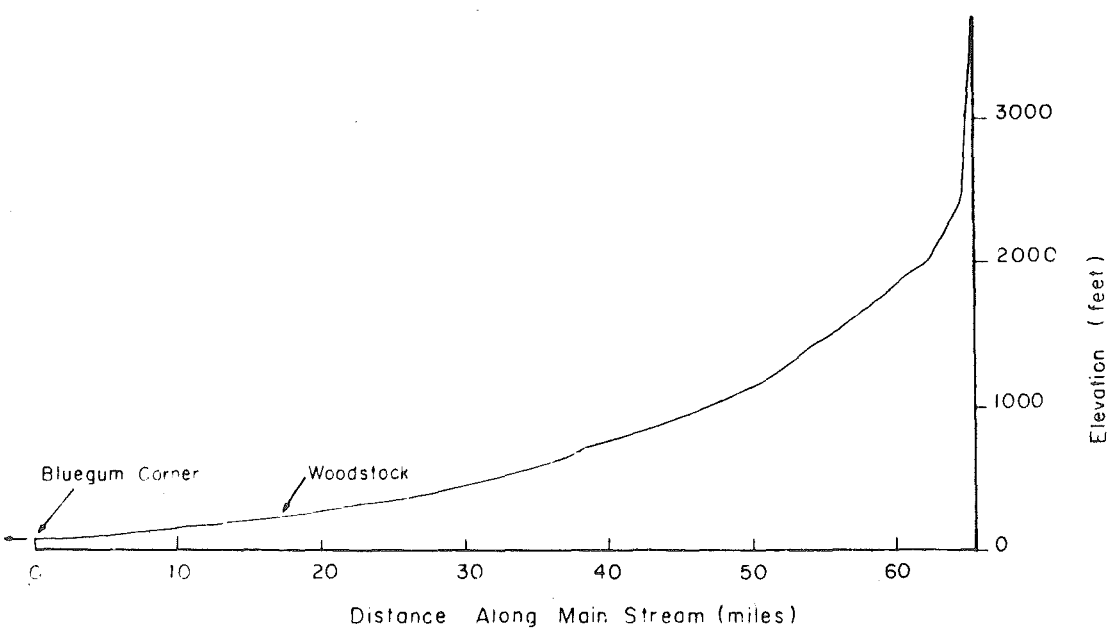


FIG. 4.13: **MOTUEKA CATCHMENT** — **Longitudinal Profile of Main Stream**

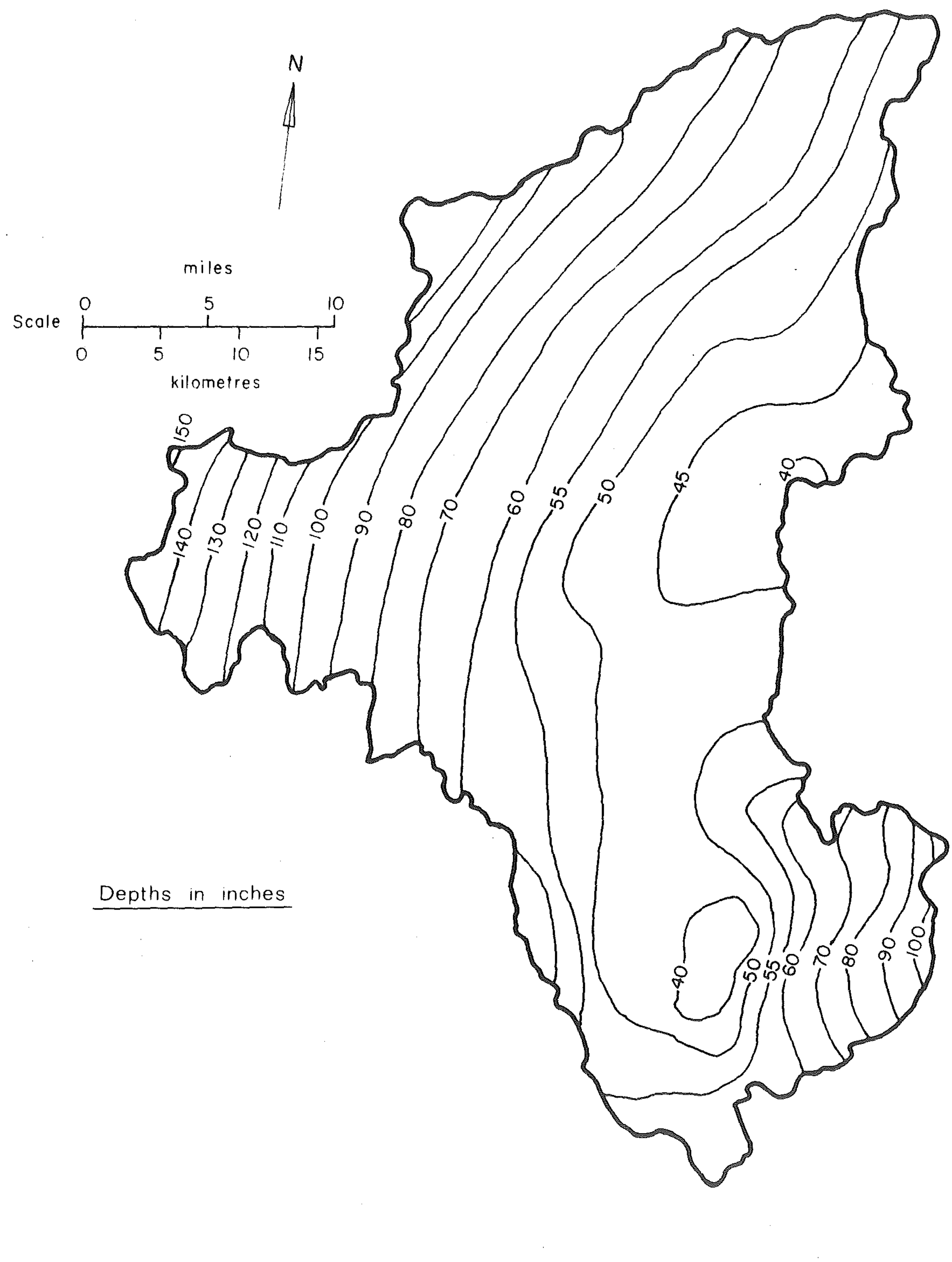


FIG. 4.14 : MOTUEKA CATCHMENT – AVERAGE ANNUAL ISOHYETAL MAP

4.1.3 Catchment Condition

For an analysis of the variation in loss rate with catchment condition the geology and land uses of the Motueka catchment were categorised into classes.

The geology was divided into seven classes (see Figure 4.15) according to probable infiltration capacity, with class I considered almost impervious and class VII highly pervious. The distinction between the classes is broad and arbitrary, and some overlapping of infiltration properties occurs amongst them. The actual geology of each class and the breakdown of the classes in each catchment are given in Appendix A, Tables A1 and A2.

The different land uses in the catchment for the period 1969 and 1970 are illustrated in Figure 4.16. The areas designated as grass in Figure 4.16 refer to all cultivated and agricultural land. From the breakdown of the land uses in each catchment (Appendix A, Table A3) it can be seen that just over 50 percent of the Motueka catchment was in forest. The two types of forest, namely exotic and native, consisted mainly of the Beech and Pinus radiata species,respectively.

4.1.4 Hydrological Data

The continuous water-level recordings at the gauging stations coupled with regular gaugings enabled reliable streamflow hydrographs to be determined on an hourly scale.

Rainfall intensities were recorded by up to nine pluviometers, whose locations are shown in Figure 4.17. Also shown are the locations of twenty two storage raingauges, which were read daily at 9 a.m.

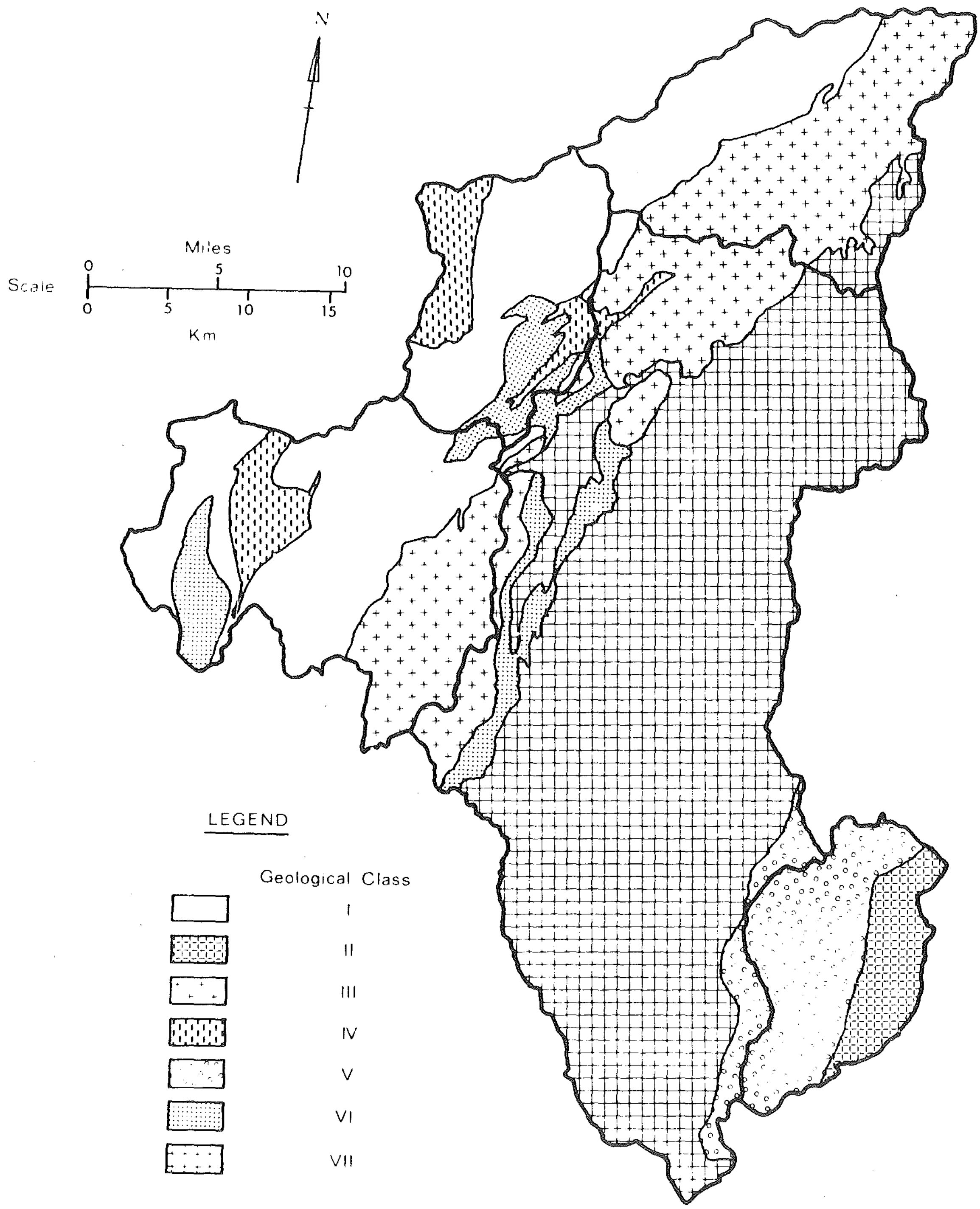


FIG. 4.15 : MOTUEKA CATCHMENT — Geological Classes

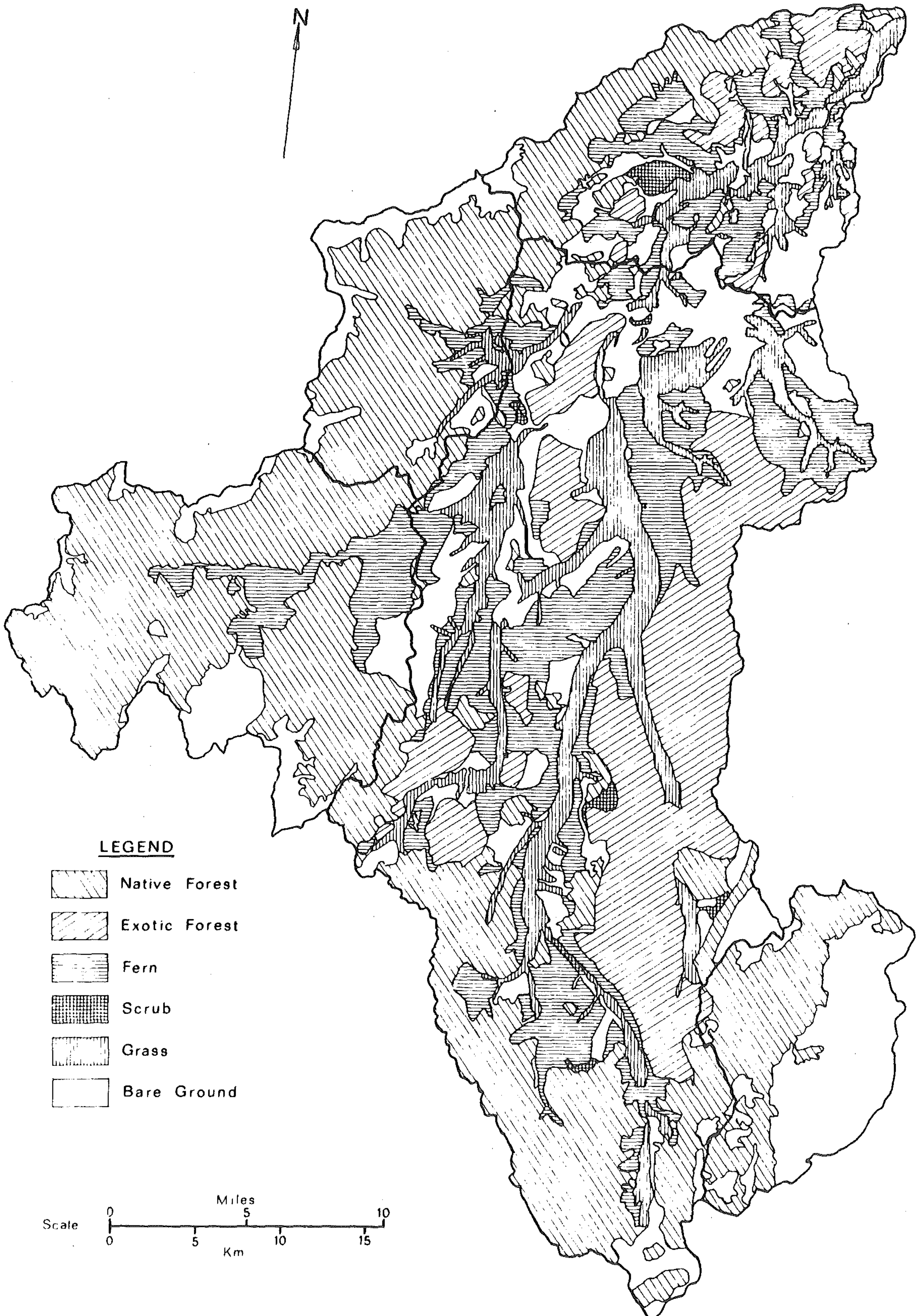


FIG. 4.16: MOTUEKA CATCHMENT — Land Uses

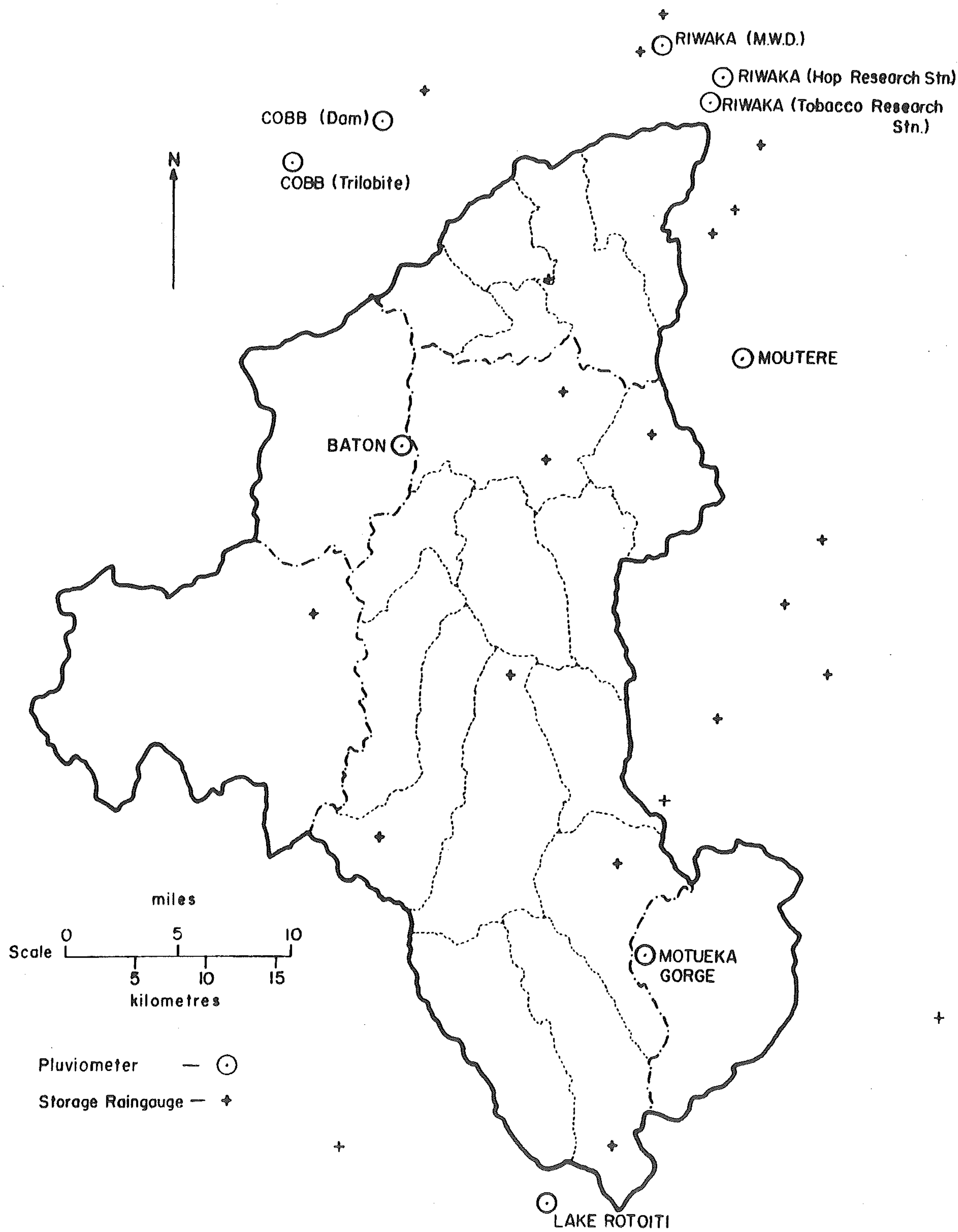


FIG. 4.17 : MOTUEKA CATCHMENT — RAINGAUGE LOCATIONS

Records were normally available for at least five pluviometers for each storm analysed. When a timing error occurred in a pluviometer record, the error was apportioned linearly over the offending period.

Though there were no data on bed load, suspended sediment data were available for the Woodstock gauging station. On fifteen separate occasions, from 1965 to 1967, depth-integrated samples (Toebes, 1963) were taken at regularly spaced points across the river at Woodstock and the suspended sediment discharge was subsequently determined. By relating the suspended sediment discharge to the corresponding streamflow discharge at the time of the sampling, the following suspended sediment rating curve was obtained for Woodstock.

$$G_s = 2.545 \times 10^{-6} \, q_T^{2.273} \qquad \text{..........} \; 4.1$$

where G_s = suspended sediment discharge, in tons/day.

The correlation coefficient for Equation 4.1, calculated from the natural logarithmic values for the two variables, is 0.96.

4.2 THE MOTUEKA MODEL

4.2.1 General

The Motueka model comprised five constituent models, i.e. one for each constituent catchment, and reproduced the surface runoff hydrograph at each gauging station. The composition and overall structure of the model are illustrated in Figure 4.18.

The upstream catchments of Upper Motueka, Wangapeka and Baton were modelled by the isochronal approach and the two minor catchments by the

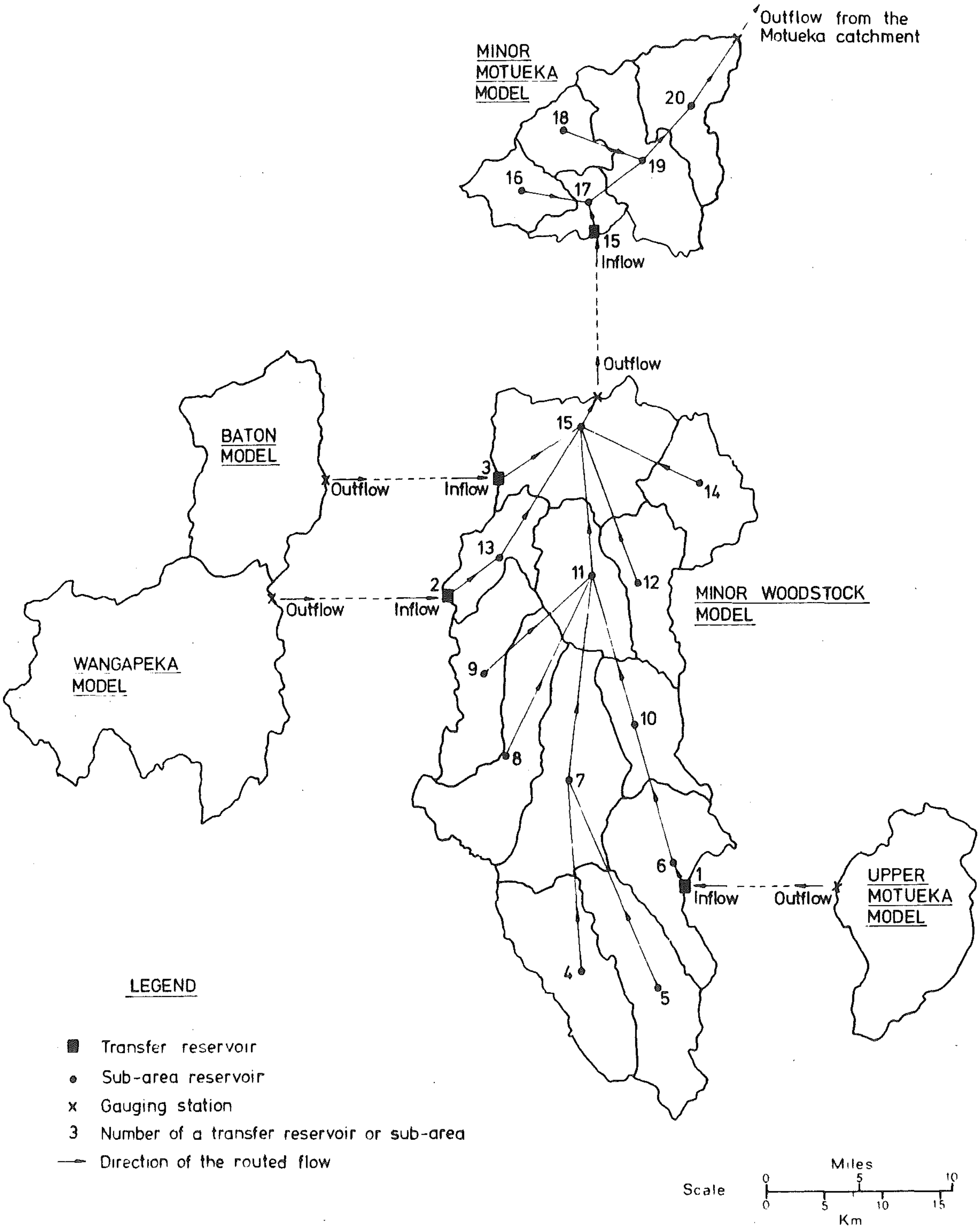


FIG. 4.18 : MOTUEKA MODEL – COMPOSITION AND ROUTING PATTERN

sub-catchment approach. This arrangement was based on the assumption that, in practice, the tendency would be to apply the isochronal approach to small catchments and the more easily constructed sub-catchment approach to large catchments.

The operations and structure for each model were the same as in the original Laurenson model, except for two modifications. The modifications are described below along with other aspects of the models.

4.2.2 Modifications

4.2.2.1 Sub-Area Patterns

The first modification arose from consideration of the Laurenson isochronal model (Figure 3.2a). In this model the flow is confined to a single, hypothetical channel, irrespective of the number of major tributaries within the catchment. This superimposing of the flows from the tributaries is not valid, in view of the non-linearity of Equation 3.11. Because the equation describes the delay time of flow through the model as decreasing with increasing discharge, the superimposition of the tributary flows reduces the delaying and attenuating capacity of the model. Thus, theoretically, the net result is a routed surface runoff hydrograph that is insufficiently attenuated and delayed.

In an attempt to remedy this possible deficiency of the Laurenson model, the isochronal sub-area patterns for the Upper Motueka, Wangapeka and Baton catchments were modified so that the model flow patterns more closely approximated the actual drainage system (see Figures 4.19-4.21). The areas and numbering system for the sub-areas of the three catchments are given in Appendix B.

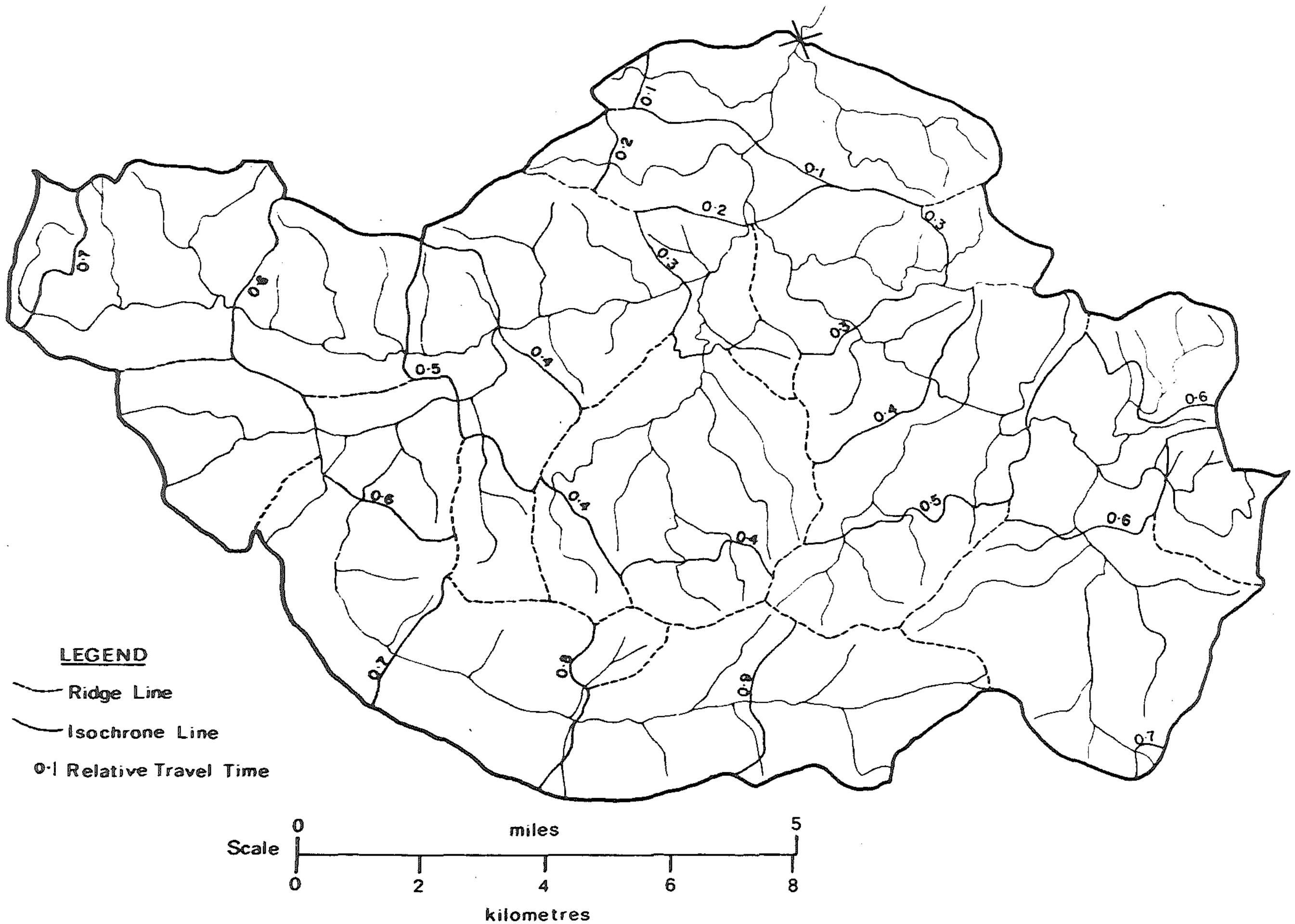


FIG. 4.19 : UPPER MOTUEKA CATCHMENT – Drainage Pattern and Modified Isochronal Sub-Areas

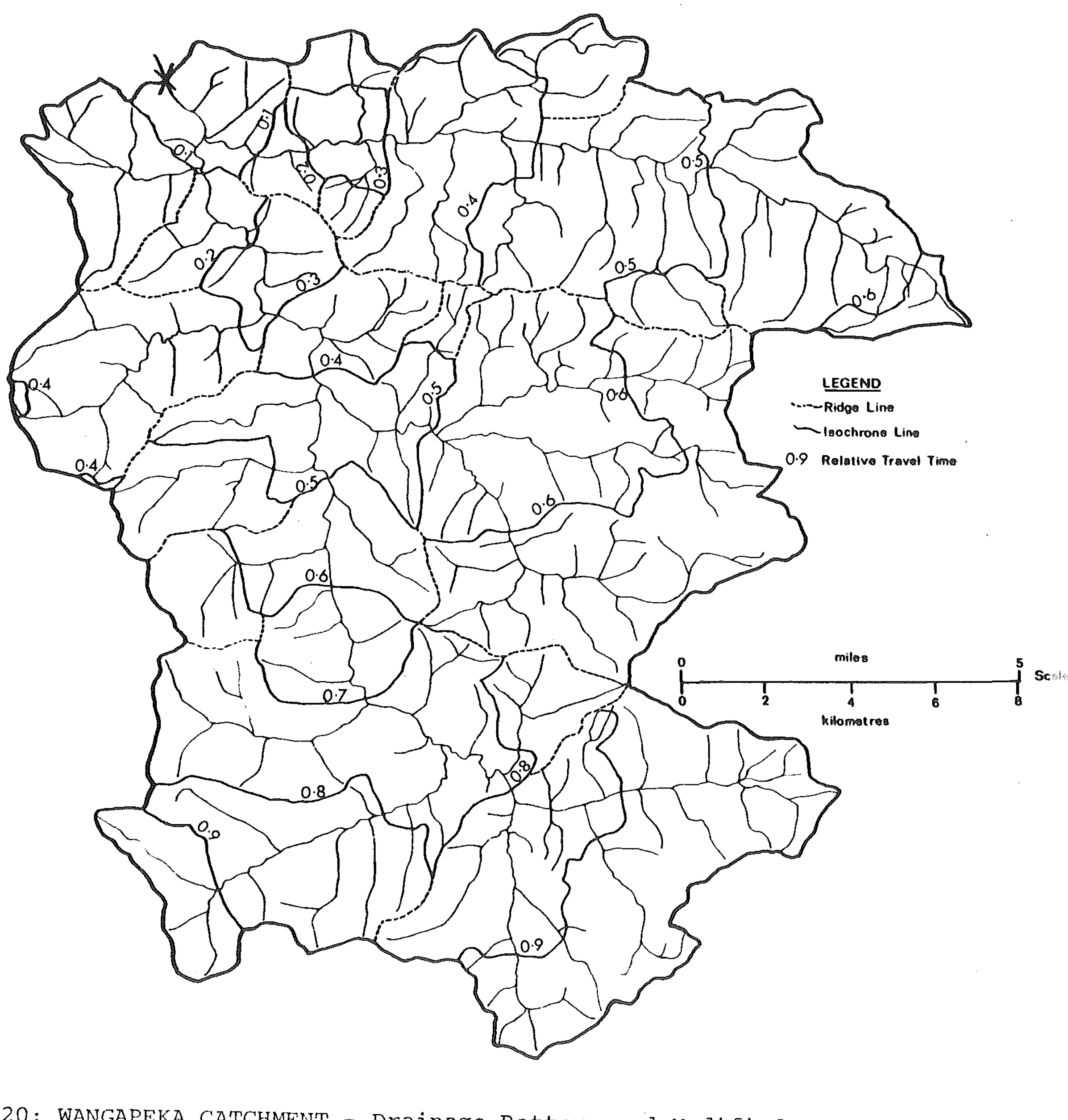


FIG.4.20: WANGAPEKA CATCHMENT - Drainage Pattern and Modified Isochronal Sub-Area

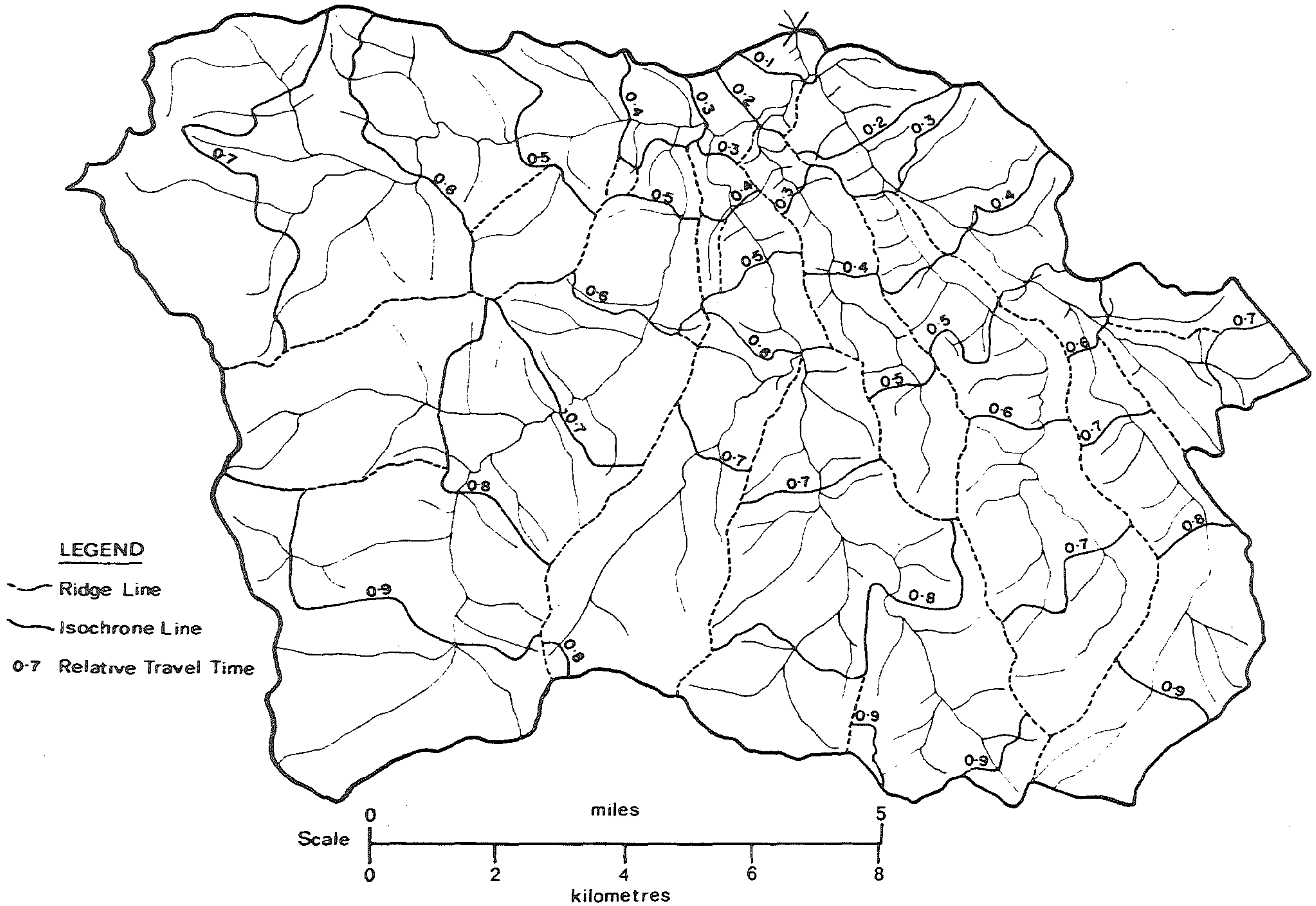


FIG. 4.21 : BATON CATCHMENT — Drainage Pattern and Modified Isochronal Sub-Areas

The isochrones were constructed as in the Laurenson model, but wherever a ridge line made an isochrone discontinuous, the discontinuity was retained. The construction criterion adhered to was that no two streams, evident in Figures 4.19-4.21, could pass completely through a sub-area without joining in that sub-area.

Because sub-catchment sub-areas inherently achieve a better approximation of the drainage system than isochronal sub-areas, the construction of the sub-area patterns for the models of the two minor catchments was much more flexible. However, this flexibility was constrained to the extent that each sub-area was constructed so that its centroid fell on or very near to the main channel in the sub-area. The constraint ensured that the reservoirs could later be located on the main channels without seriously infringing the concept of the sub-catchment approach. Locating the reservoirs on the main channels makes the catchment model more realistic, in that the relative travel times along the model flow reaches are then the same as those for the corresponding reaches of the main channels. Without the constraint it is possible to obtain quite unrepresentative relative travel times for the model flow reaches.

4.2.2.2 <u>Optimisation</u>

The second modification concerned the reservoir delay time-discharge equation (Eq. 3.11). In the original Laurenson model the equation is applied with always the same A and B values to describe all flood events in a catchment. The implication is that the travel time-discharge relationship (Eq. 3.9), on which Equation 3.11 is based, is invariant. However, it is more reasonable to expect that the relationship depends on the particular storm and varies with such storm characteristics as the spatial and temporal and distribution of rainfall excess.

To allow for the probable variation in the travel time-discharge relationship, an automatic optimisation technique was built into the Motueka model. The technique was of the type developed by Rosenbrock (1960) and described by Dawdy and O'Donnell (1965) and Jamieson et al (1972). It was used to optimise the A and B values in the reservoir delay time-discharge equation (Eq. 3.11), so that the best possible surface runoff hydrograph was obtained from a constituent model for the storm concerned.

4.2.3 Relative Travel Times

In calculating the relative travel times for points in the constituent catchments (see Section 3.4.2 for the method), 100 ft (30.5 m) contour intervals were used when the altitude was less than 1000-1500 ft (300-450 m). At greater altitudes the 100 ft contours were closely spaced and it was practical to work only on a contour interval of 500 ft (152.5 m).

For each constituent catchment the calculated travel times were made relative to the maximum time calculated for the corresponding true catchment. This took account of the travel time of the flow in the constituent catchment(s) upstream of a minor catchment, and so ensured that the routing of flow through a minor model only accounted for the travel time of the flow in the minor catchment.

Similarly, in determining the Y value for a constituent catchment it was necessary to consider the effect of the whole catchment on the flow in the constituent catchment. Hence the Y value for the Minor Motueka catchment, for example, was that pertaining to the whole Motueka catchment. Consequently, in calculating Y for the Minor Motueka catchment from Equation 3.2, the twenty main sub-areas within the Motueka catchment were considered with the Upper Motueka, Wangapeka and Baton catchments each treated as a singl sub-area. And the relative travel times used in Equation 3.2 were those for the sub-area reservoirs or, in the cases of the Upper Motueka, Wangapeka and Baton catchments, those for the sub-area (i.e. catchment) centroids.

4.2.4 Reservoir Locations

4.2.4.1 Upper Motueka, Wangapeka and Baton Models

In the Laurenson isochronal model (Figure 3.2a) the reservoirs are located at the sub-area centres, where the term centre refers to a point that represents the average of the relative travel times of a sub-area's upstream and downstream boundaries. This definition of centre was adopted for the models of the Upper Motueka, Wangapeka and Baton catchments when a sub-area was bounded by isochrones both upstream and downstream. However, when a ridge line formed the upstream boundary, the centre was taken as a point near the sub-area centroid with a relative travel time close to the sub-area average.

4.2.4.2 Minor Woodstock and Minor Motueka Models

The reservoirs in the models of the two minor catchments were located on the main channels at points nearest to the sub-area centroids. The locations are shown in Map 1.

The reservoir in sub-area no. 15 (the sub-area immediately above Woodstock) was later shifted, when it was observed that the relative travel time from the Baton outlet to Woodstock (0.156) was less than that from the reservoir to Woodstock (0.164). Thus the outflow from the Baton model would have travelled in a reverse or upstream sense to the reservoir if its location remained as shown in Map 1.

The anomaly was caused by the fact that the channel slope from the Baton outlet to Woodstock is steeper than that of the main branch of the Motueka river between the original reservoir location and Woodstock. The problem was overcome by re-locating the reservoir at the confluence of the Baton and Motueka rivers.

4.2.4.3 Details

The relative travel times for the reservoirs of all the constituent models are contained in Appendix B.

4.2.5 Runoff Routing

The runoff routing procedure in the Motueka model is explained diagrammatically in Figure 4.22. The direction of the routed flow in the model is indicated in Figure 4.18. Within each constituent model the direction of the flow was from the lower numbered to the higher numbered sub-area immediately downstream.

The so-called transfer reservoirs in Figure 4.18 received no rainfall excess from their sub-areas; their purpose was to transfer the outflow from the upstream model into the one concerned.

The mathematical procedure of routing runoff through a reservoir in the Motueka model involved Equations 3.12-3.16 and followed the method described by Laurenson (1962, 1964). The only difference was that the iterative solution, for the outflow discharge q_2 from the reservoir at the end of a routing period, was continued until the variation between successive values of the corresponding delay time K_2 was less than 1 percent. In the Laurenson model only two iterations were used to obtain the outflow discharge

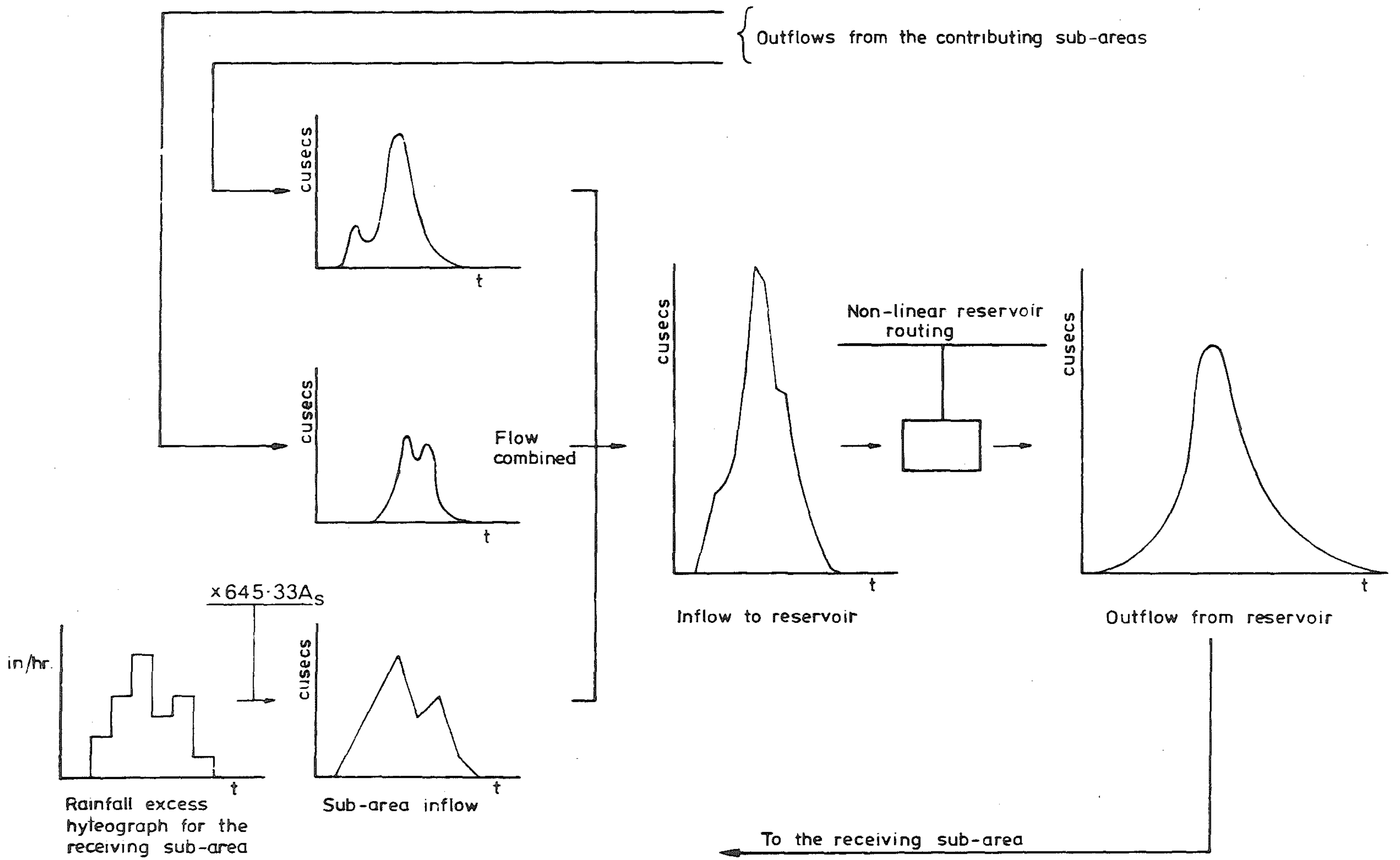


FIG. 4.22 : ILLUSTRATION OF THE GENERAL ROUTING PROCEDURE

4.2.6 Data for the Model

The following data were required for the operation of the Motueka model.

(a) The pattern and areas of the sub-areas.

(b) The relative travel times for the reservoirs.

(c) Sediment rating curves for the gauging stations.

And for each storm

(d) The surface runoff hydrographs for the gauging stations.

(e) The loss rates for the constituent catchments.

(f) The rainfall excess hyetographs for the sub-areas in each constituent catchment.

(g) Initial estimates of A and B for the constituent catchments.

This chapter has covered items (a) to (c). The remaining items are dealt with in Chapter 5.

CHAPTER 5

ANALYTICAL PROCEDURE

Hydrological data were obtained on the sixteen Motueka storms of 1969 and 1970 that were adequately recorded. The data were restricted to two years so that the land-use situation remained essentially constant for the study period.

This chapter describes the preparation of the storm data for their possible use in the Motueka model and also for a regression analysis of loss rate on storm and catchment variables. The data preparation involved the determination of: the surface runoff hydrographs (Section 5.1); the loss rates and the sub-area rainfall excess hyetographs (Section 5.2); and initial estimates of A and B (Section 5.3).

The chapter also covers: the adaptation of the optimisation technique (Section 5.4); the goodness-of-fit criteria for evaluating the performance of the model (Section 5.5); the sensitivity analyses performed (Section 5.6), and methods used in a statistical analysis of the loss rate (Section 5.7). At the end of the chapter (Section 5.8), a summary of the analytical operations is given and reference is made to computer programs.

5.1 RUNOFF HYDROGRAPH ANALYSIS

5.1.1 General

Total runoff may comprise up to three flow components at any instant (see Figure 5.1). The differentiation between the components is arbitrary and somewhat artificial, and is made in terms of their relative response,

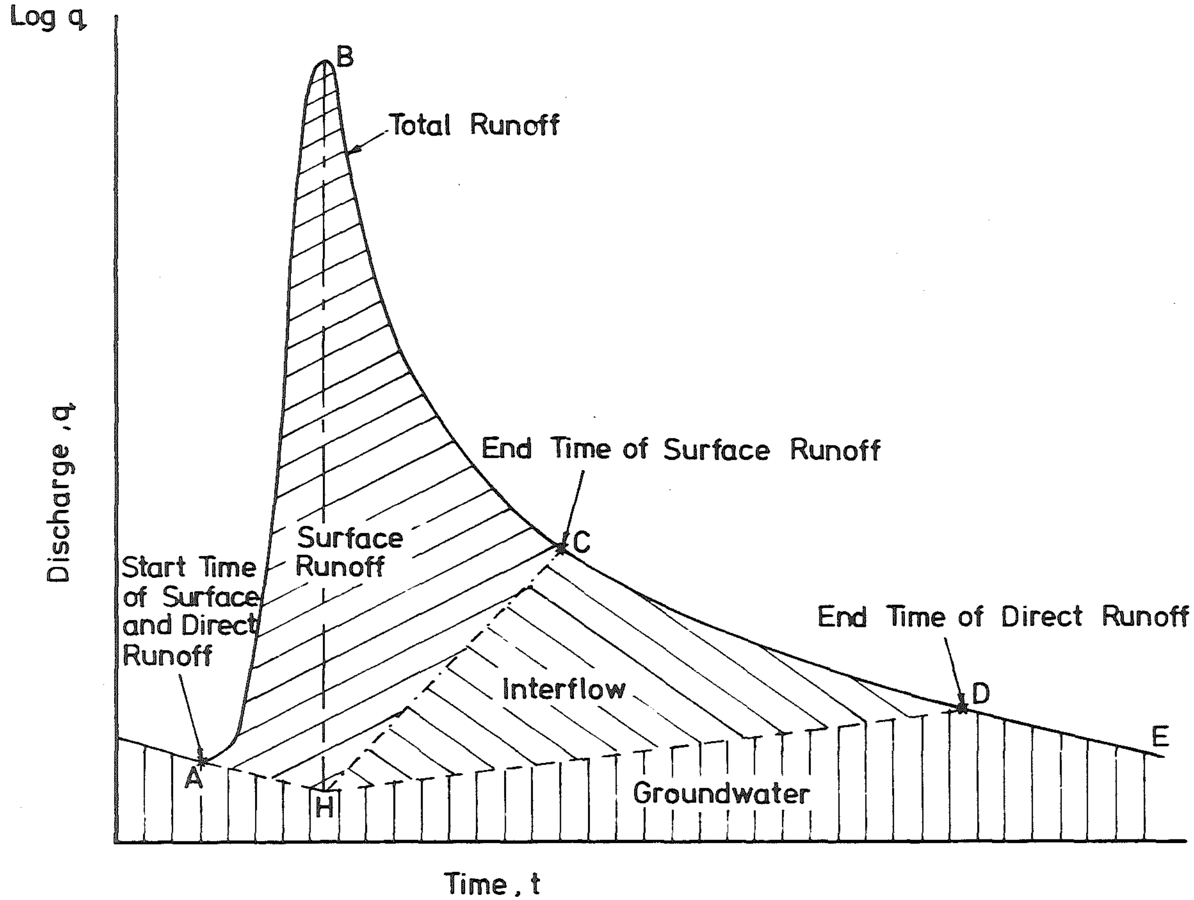


FIG. 5.1 : A DIFFERENTIATION OF STREAMFLOW COMPONENTS

as observed at the catchment outlet, to rainfall input (see Table 5.1).

TABLE 5.1

A DIFFERENTIATION OF STREAMFLOW COMPONENTS

Response	Flow component	Combinations of flow components
Fast	Surface runoff	Direct runoff
Delayed	Interflow	Baseflow
Slow and frequently continuous	Groundwater	

The separation of the surface runoff hydrographs from the total runoff hydrographs received considerable attention in this study because it affected all the subsequent results. Wherever possible, at least two methods were used in the separation process, with each method providing a check on the results from the other.

For each total runoff hydrograph the time limits of direct runoff and surface runoff were defined. A baseflow hydrograph was then inserted between the latter limits and subtracted from the total runoff hydrograph to produce the surface runoff component. A fuller description of this separation procedure follows in Sections 5.1.2-5.1.4.

5.1.2 Time Limits of Direct Runoff

The end times of direct runoff were defined by analysing the recessions of the total runoff hydrographs in two ways.

In the first method the recessions were plotted on semi-log paper, with discharges to the log scale. The plotting was based on the usual assumption that the recession of a flow component is linearised by semi-log paper, since the recession represents depletion from storage and thus should conform to the decay equation

$$q_t = q_o k_r^{\ t} \qquad \text{.......... 5.1}$$

where q_o and q_t are the discharges at times 0 and t, respectively, and k_r is a depletion ratio constant; the slope of the straight line on semi-log paper is equal to log k_r.

Because each flow component depletes a different storage, the semi-log plot of a total runoff recession theoretically should be a curve with a gradually decreasing slope, until only the groundwater component is present. However, for practical purposes the recession can often be approximated by three straight lines, i.e. one line for total runoff, one for direct runoff and one for groundwater.

In the present case the plotted total runoff recessions could be approximated by straight lines, though three were often insufficient. Nevertheless, the tail of each recession was straight and its commencement gave the first indication of the end time of direct runoff (see Figure 5.2).

In the second method of analysing the total runoff recessions, a composite or master groundwater recession curve was constructed from and then applied to the total runoff recessions of each gauging station, in a manner as described by Linsley et al (1958, p.154). This produced the end times of direct runoff. The times were checked that they agreed closely with those indicated by the first method.

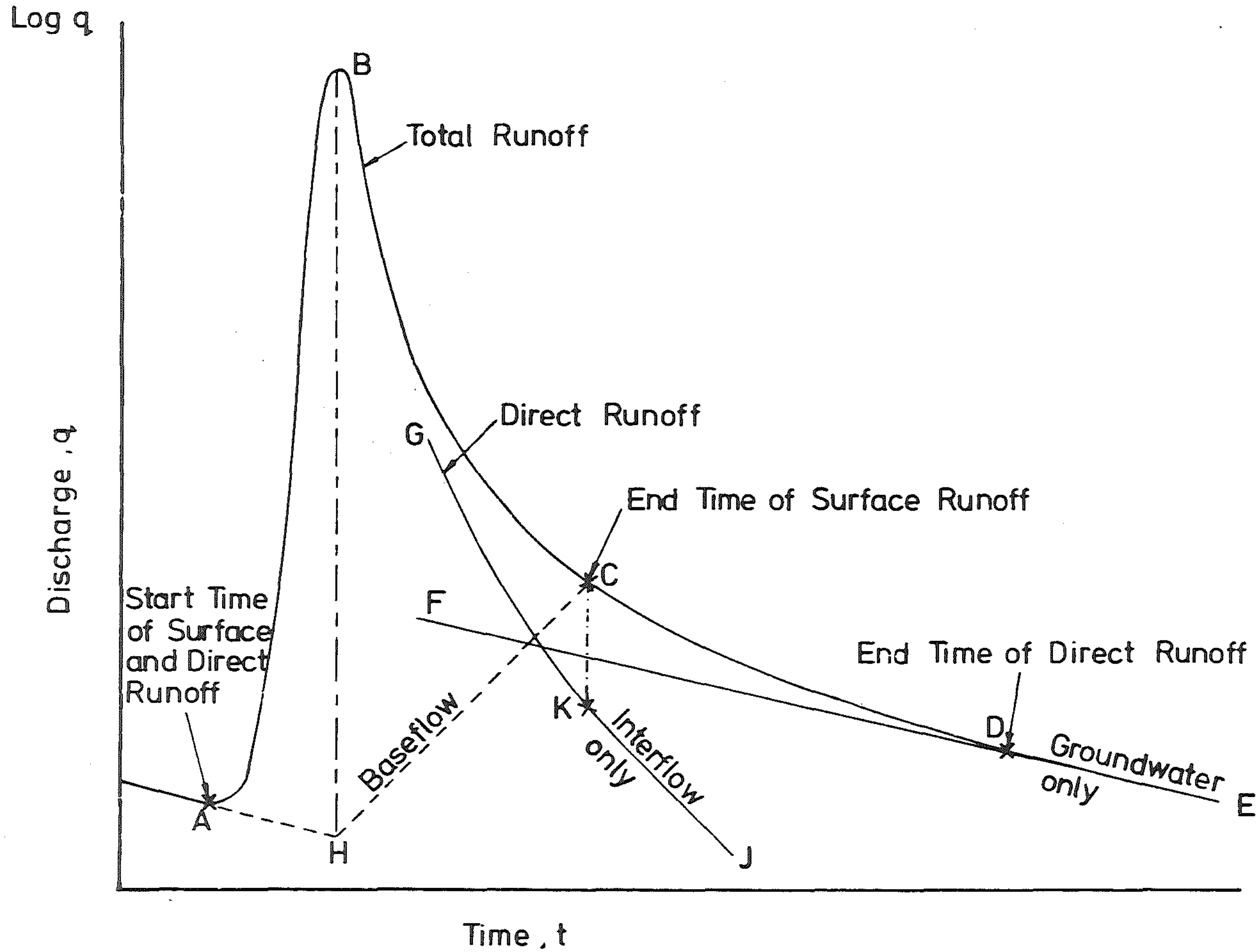


FIG. 5.2 : A METHOD OF OBTAINING SURFACE RUNOFF

The definition of the start times of direct runoff was much easier. The start time was the point where the first hydrograph rise departed from the groundwater recession in the early part of the hydrograph, e.g. point A in Figures 5.1 and 5.2.

5.1.3 Time Limits of Surface Runoff

The start times of surface runoff were the same as those for direct runoff (see Figure 5.1 or 5.2).

The end times of surface runoff were defined after an analysis of the direct runoff recessions. Two approaches were used to obtain the recessions. They each produced the recessions by subtracting groundwater from the total runoff recessions,but differed in their assumption of the shape of the groundwater hydrograph. One approach assumed the shape given as the line HD in Figure 5.1. The other approach followed that described by Karoly (1965) and assumed the shape given as the line FD in Figure 5.2.

The resulting two sets of recessions were analysed by two methods, giving four estimates of the end time of surface runoff for each total runoff hydrograph. In the first method each recession was plotted on semi-log paper and then inspected for the point where the linearisation of the tail commenced, e.g. point K in Figure 5.2. The second method employed the master recession curve technique (Section 5.1.2), only this time the master curves were of interflow not groundwater.

The four estimates of the end time generally lay within a six hour range; the range was less than 10 percent of the length of the corresponding surface runoff hydrograph. The estimate most representative of the four was taken as the end time of surface runoff.

5.1.4 Surface Runoff Hydrographs

For a single-peak total runoff hydrograph, the corresponding surface runoff hydrograph was obtained by subtracting baseflow, of the hydrograph shape AHCDE in Figure 5.2, from the total runoff.

The multi-peak hydrograph case was more complex, and the obtaining of the surface runoff hydrographs for the individual rises is described in stages below.

Stage 1

The presence of the surface runoff component in a multi-peak total runoff hydrograph was identified by defining the normal and so-called intermediate start and end times of surface runoff (see Figure 5.3). The intermediate times were defined from a study of the maximum baseflow rates for the gauging station, and from an inspection of the semi-log plot of the total runoff hydrograph.

Stage 2

The master surface runoff recession curve for the gauging station was constructed from the surface runoff recessions of the relevant single-peak hydrographs.

Stage 3

Subtraction of baseflow, of the hydrograph shape A-I in Figure 5.3, from the total runoff and the application of the appropriate master surface runoff recession curve produced the individual surface runoff

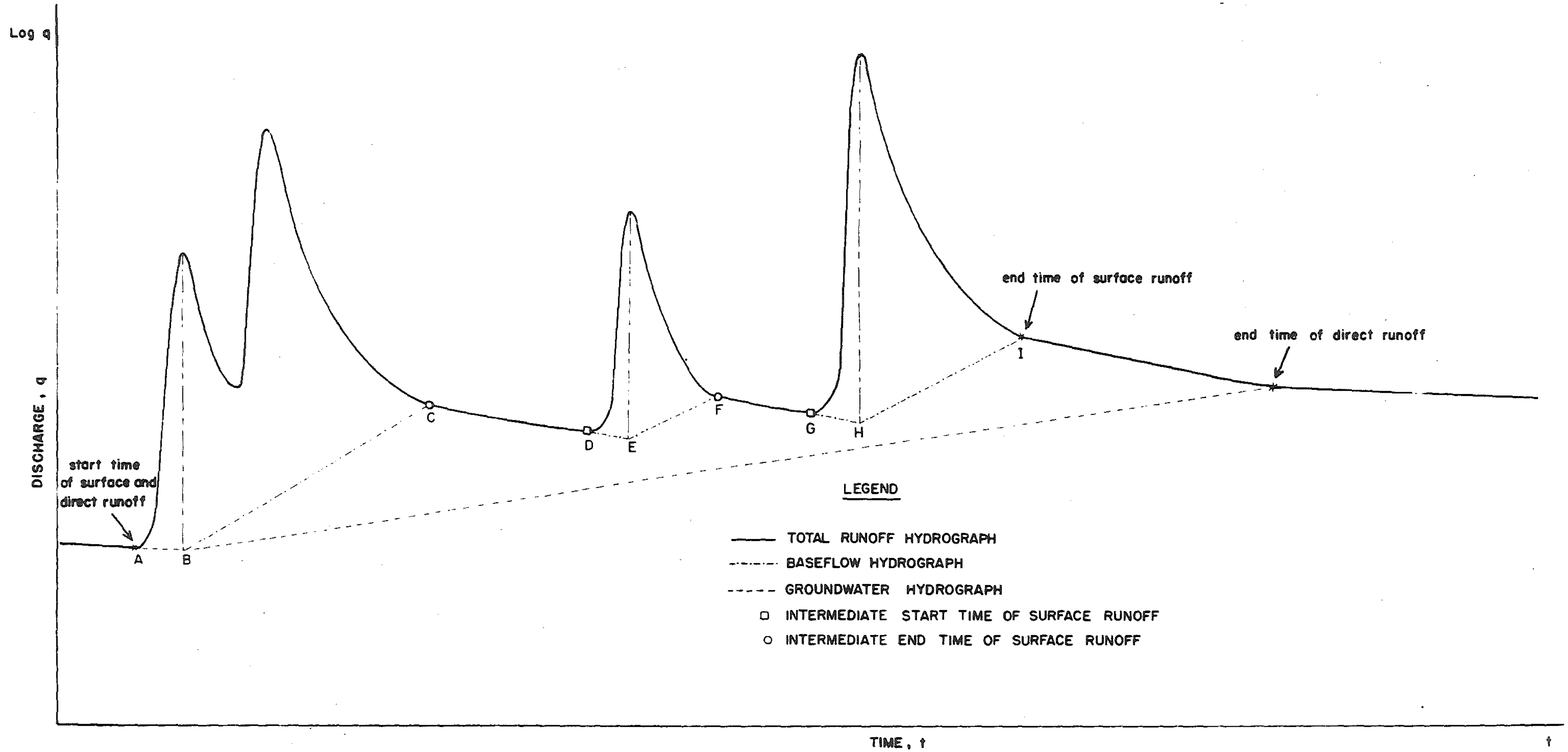


FIG. 5.3 : THE GROUNDWATER AND BASEFLOW HYDROGRAPHS FOR A MULTI-PEAK TOTAL RUNOFF HYDROGRAPH

hydrographs (see Figure 5.4). Starting with the first rise, the procedure was to:

(a) subtract baseflow up to the point where the total runoff recession was disturbed by rain; and

(b) apply the master curve from this point onwards to complete the recession of the surface runoff hydrograph.

The same process was repeated for the subsequent rises, although the surface runoff recessions from the preceding rises were subtracted along with baseflow from the total runoff, when appropriate.

An actual example of a multi-peak hydrograph and its separated surface runoff hydrographs is shown in Figure 5.5.

5.2 RAINFALL ANALYSIS

5.2.1 General

The other main type of input data to the model, in addition to streamflow, was storm rainfall in the form of sub-area rainfall excess hyetographs. The determination of the hyetographs is the subject of Sections 5.2.2-5.2.6.

For uniformity, the surface runoff hydrograph at Bluegum Corner was used to ascertain the time limits of a storm. All the rainfall and runoff which contributed to that hydrograph were considered as belonging to the one storm.

5.2.2 Isohyetal Maps

An isohyetal map was constructed for each storm from the rainfall depths recorded by the pluviometers and the daily-read storage raingauges.

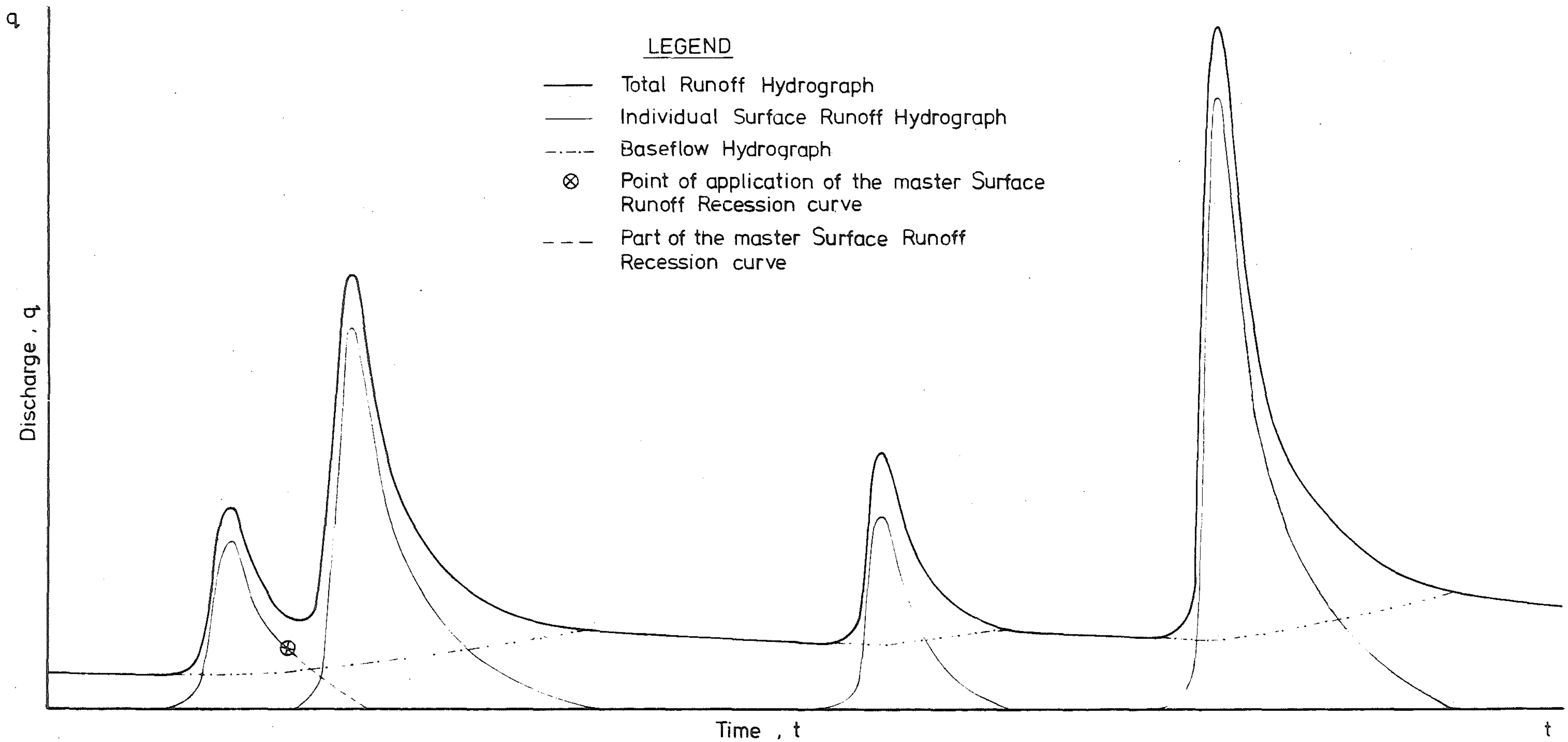


FIG. 5.4 : THE INDIVIDUAL SURFACE RUNOFF HYDROGRAPHS FOR THE MULTI-PEAK HYDROGRAPH IN FIG. 5.3

DETAILS

Example is for Woodstock

Time Datum = 1200, 16/12/69

× Point of application of the master surface runoff recession curve

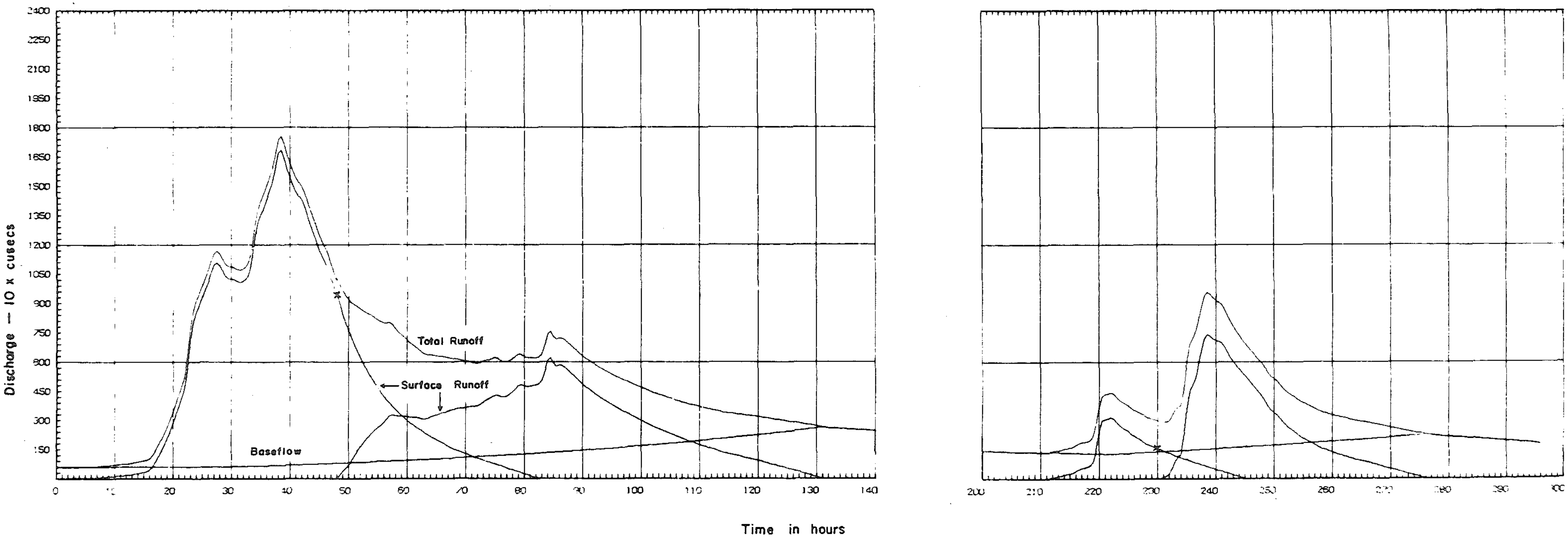


FIG. 5.5 : AN ACTUAL EXAMPLE OF SEPARATED SURFACE RUNOFF HYDROGRAPHS

Because the time limits of a storm rarely coincided with the 9 a.m. readings of the storage raingauges, it was unavoidable that an isohyetal map usually included extraneous rainfall.

Where rainfall information was unavailable or inadequate, it was often necessary to make the storm isohyetal pattern similar to the average annual pattern.

5.2.3 Sub-Area Rainfall Hyetographs

For each storm, rainfall hyetographs were obtained for the sub-areas in the following manner.

(a) Each sub-area was allotted the hourly hyetograph pattern of a pluviometer, usually the nearest. The duration of the hyetograph was the same as that of the isohyetal map.

(b) The ordinates of each sub-area's hyetograph were linearly adjusted so that the sub-area's rainfall total equalled that as indicated by the isohyetal map.

(c) Rainfall bursts outside the storm's time limits were eliminated.

5.2.4 Storm Rainfall Characteristics

To facilitate the loss rate derivations, as well as to enable an examination of the loss rate's relationship with storm variables, the storm rainfall characteristics of depth, duration and intensity were quantified for the five constituent catchments and also for the Woodstock and Motueka catchments.

The catchment rainfall depth DEPTH was calculated as the sub-area average, but weighted with respect to area, from

$$\text{DEPTH} = \frac{\sum_{i=1}^{nr} d\ A_s}{\sum_{i=1}^{nr} A_s} \qquad \text{.......... } 5.2$$

where d = the rainfall total of the sub-area rainfall hyetograph, in inches;

and nr = the number of sub-areas in the catchment that received rainfall.

The average duration of storm rainfall in a catchment (DURTN) was calculated similarly, but the weighting was with respect to area and rainfall depth. Thus

$$\text{DURTN} = \frac{\sum_{i=1}^{nr} du\ d\ A_s}{\sum_{i=1}^{nr} d\ A_s} \qquad \text{.......... } 5.3$$

where du = the duration of the sub-area rainfall hyetograph, excluding the periods of no rainfall, in hours.

The average storm rainfall intensity INT for a catchment was calculated as the ratio of the catchment storm rainfall depth to the corresponding duration.

In obtaining the average depth, duration and intensity for the Woodstock and Motueka catchments, the upstream catchments of Upper Motueka, Wangapeka and Baton were treated as single sub-areas. Thus, twenty sub-areas were considered in the case of the Motueka catchment. This same procedure was used in deriving the loss rate (Section 5.2.5) and lag (Section 5.3) for the two catchments.

5.2.5 Loss Rate Derivation

After classifying some rainfall bursts in a storm as initial loss (Section 5.2.3, part c), loss rates were derived for the constituent catchments and also for the Woodstock and Motueka catchments.

The method of deriving the loss rate was similar to that outlined by Horton (1937) and Laurenson (1954), but was adapted for a computerised solution. The fundamental operation of the method was the trial-and-error adjustment to the loss rate value, until the equivalent depth of the recorded surface runoff volume was matched by the computed rainfall excess depth. The method accounted for differences in the sub-area hyetographs and for the case of the partial-area storm. Attention was also given to those storms where certain sub-areas, though receiving rainfall, do not contribute to surface runoff.

In deriving the loss rate for a minor catchment the *net* surface runoff volume was used. This was the surface runoff volume recorded as outflow from the catchment, less the corresponding volume(s) recorded as inflow.

The flow diagram in Figure 5.6 illustrates the method used to derive the loss rate for a catchment. The rainfall excess variables of depth (REDEPTH) and duration (REDURTN) mentioned in Figure 5.6 were calculated by equations analogous to those (Eqs. 5.2 and 5.3) used in calculating the corresponding rainfall variables. Variables not defined in Figure 5.6 are:

VSR = volume of recorded surface runoff, in cusec-hours;

and DSR = the equivalent depth of surface runoff, in inches.

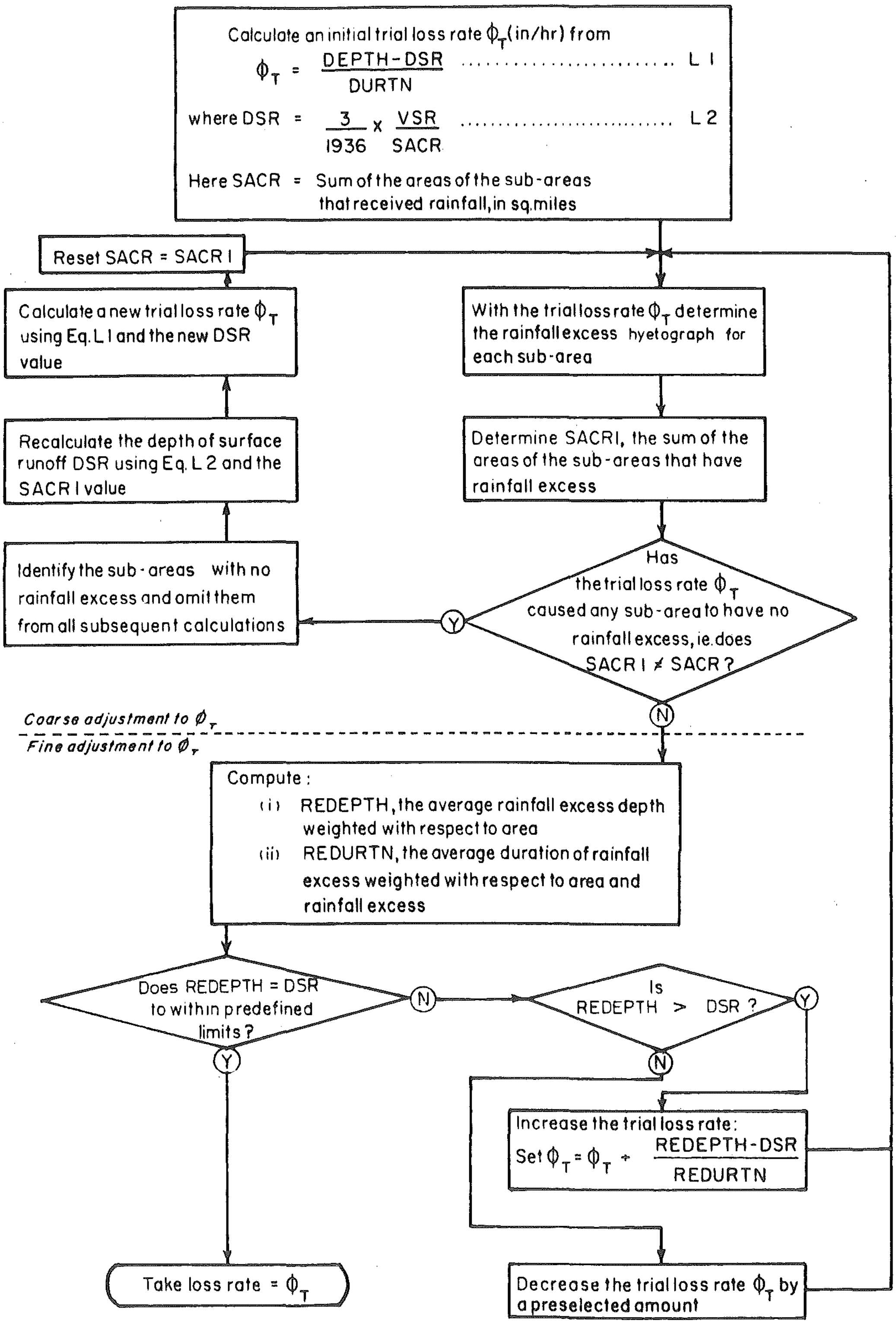


FIG. 5.6 : FLOW DIAGRAM OF THE DERIVATION OF THE LOSS RATE

5.2.6 Sub-Area Rainfall Excess Hyetographs

The rainfall excess hyetographs for the sub-areas in a constituent catchment were obtained in the derivation of the loss rate, when the loss rate was applied to the sub-area rainfall hyetographs.

5.3 LAG-MEAN DISCHARGE RELATIONSHIPS

Some attention was paid to obtaining reasonable initial estimates of A and B for the optimisation within each constituent model. One reason for this was that an optimisation technique is more likely to yield the optimum solution if the initial values are near to the optimum ones (e.g. Ibbitt and O'Donnell, 1971).

A second reason was the length of time involved in running the computer program of the Motueka model. Each optimisation step in a constituent model involved the computation of the routed surface runoff hydrograph, and this computation time was significant (see Appendix C). It appeared that reasonable initial estimates of A and B would reduce the computer running costs by reducing the number of optimisation steps required.

Lag-mean discharge relationships in the form of Equation 3.7 were therefore sought for the true catchments. If such relationships were found the coefficients and the absolute exponent values of the equations could then be used as initial estimates of A and B for the models of the corresponding constituent catchments. An additional purpose in seeking these relationships was that their existence would indicate the feasibility of carrying out a study like Askew's (1968a,b) on New Zealand catchments, so that the Laurenson model could be applied to ungauged catchments in this country.

The lag and mean discharge for the true catchments were therefore calculated for each of the sixteen storms. Catchment lag L was calculated as the sub-area average, but weighted with respect to area and rainfall excess, from

$$L = \frac{\sum_{i=1}^{nr} l_s A_s RE}{\sum_{i=1}^{nr} A_s RE} \qquad \text{.......... 5.4}$$

where l_s = the sub-area lag in hours, i.e. the difference in time between the centroids of the sub-area rainfall excess hyetograph and the surface runoff hydrograph;

and RE = the sub-area's rainfall excess depth.

The mean discharge $\bar{q}_{TS}$ was calculated on an hourly basis from the following equation, which is similar to that (Eq. 3.4) used by Askew (1968a,b) except that surface runoff is considered instead of direct runoff.

$$\bar{q}_{TS} = \frac{\sum_{i=1}^{n} q_T \, q_S}{\sum_{i=1}^{n} q_S} \qquad \text{.......... 5.5}$$

where $\bar{q}_{TS}$ = the weighted mean rate of total runoff over the period of surface runoff, in cusecs;

q_S = an hourly ordinate of surface runoff;

and n = the number of hourly ordinates of surface runoff.

5.4 THE OPTIMISATION PROCEDURE

For each storm in a constituent model, optimum values for A and B in the reservoir delay time-discharge equation (Eq. 3.11) were obtained by producing the routed surface runoff hydrograph which best fitted the corresponding actual hydrograph. The fitting was done with the optimisation technique (Section 4.2.2.2). The technique was used to optimise (in this case minimise) the objective function, which was the sum of the squares of the differences of the hourly ordinates of actual and routed surface runoff. This particular function placed emphasis on the reproduction of the hydrograph peak and its time of occurrence.

Given initial values for A and B, the optimisation proceeded in cycles. Within each cycle a search was made in steps along directions parallel to a pair of orthogonal axes for A and B values that gave a minimum objective function. The axes were then rotated and the search operations repeated in the next cycle. The optimisation was terminated when:

(a) the reduction in the objective function between successive cycles was less than a specified amount (0.5-1.0%); or

(b) after the completion of eight cycles.

These terminating criteria were necessary to curtail computer running costs and were more lenient (especially the second criterion) than would otherwise be desirable. However, they only strictly applied to the two minor models. Since the other three models could be operated independently of each other, the optimisation process was repeated in one of these models when there seemed a likelihood of noticeably improving a hydrograph reproduction.

In instances where the optimum solution was yielded after only a few cycles, the optimisation was recommenced with a new initial set of A and B values and the solution that gave the best fit was taken as the optimum one. This ensured that the final solution was not totally dependent on the initial conditions.

5.5 GOODNESS-OF-FIT CRITERIA

To allow for an objective evaluation of the model performance, the goodness-of-fit of the optimum routed hydrographs was measured by the indices defined in Figure 5.7. Each summation involved in the calculation of an index was made over that period where both the actual and routed hourly instantaneous discharge exceeded the nominal flow of one cusec (0.0283 m^3/s).

The true peaks of the actual and routed hydrographs were used in the variation-in-peak index. Because the hydrographs were determined on an hourly basis, the true peaks were seldom directly obtainable. They were therefore calculated, by a quadratic interpolation method.

5.6 SENSITIVITY ANALYSIS

On the assumption that a catchment's storage effects on streamflow were simulated when the surface runoff hydrograph was satisfactorily reproduced, the sensitivity analysis technique (Section 1.4) was applied to different regions within the Motueka catchment.

The sensitivity analyses that were performed were of two types. They differed only in the form of land treatment simulated. The main type was based on a form of vegetal land treatment, like afforestation, which can be expected to increase the infiltration potential of the

Index	Formula	Comments	Good Fit	Bad Fit
Model Efficiency (Nash and Sutcliffe, 1970)	$\dfrac{\Sigma(q_a-\bar{q}_a)^2 - \Sigma(q_a-q_c)^2}{\Sigma(q_a-\bar{q}_a)^2}$	Analogous to the coefficient of determination	1	$-\infty$
Integral Square Error (March and Eagleson, 1965)	$\dfrac{(\Sigma(q_a-q_c)^2)^{\frac{1}{2}}}{\Sigma q_a} \times 100\%$	Measures vertical discrepancy - varies with length of record	0	∞
"Correlation Coefficient" (March and Eagleson, 1965)	$\left[\dfrac{2\Sigma q_a q_c - \Sigma q_c^2}{\Sigma q_a^2}\right]^{\frac{1}{2}}$	Not the statistical correlation index	1	0
Coefficient of Variation (Ibbitt and O'Donnell, 1971)	$\dfrac{(n\Sigma(q_a-q_c)^2)^{\frac{1}{2}}}{\Sigma q_a}$		0	∞
Variation in Surface Runoff Peak	$\dfrac{q_{c_{max}} - q_{a_{max}}}{q_{a_{max}}} \times 100\%$		0	$\pm\infty$

Where $\bar{q}_a = \frac{1}{n} \Sigma q_a$

q_a = actual hourly instantaneous discharge

q_c = computed (routed) hourly instantaneous discharge

and n = number of hourly instantaneous discharge values.

FIG. 5.7 DEFINITIONS OF THE GOODNESS-OF-FIT INDICES treatment region. The treatment was simulated by increasing the loss rate for the sub-areas and the parts of the sub-areas within the treatment region. Loss rate increases were made over a range of values, covering the maximum loss rate that the treatment could be expected to produce.

The second type of sensitivity analysis was based on mechanical land treatment, e.g. a series of diversion or retention dams, which would restrict the outflow of all surface runoff from the treatment region. This situation is not uncommon in New Zealand and is evident, for example, in hydro-electric power schemes which capture and reroute water to augment the flow through the power-generating system. The treatment was simulated by simply increasing the loss rate for the treatment region until all the rainfall excess there was eliminated.

At each increase of the loss rate in an analysis, two factors associated with the routed runoff were determined and then compared with their original values before the analysis began. These factors were:

(a) the true surface runoff peak; and

(b) the quantity of suspended sediment transported over the period of surface runoff.

The suspended sediment quantities were determined with the Woodstock rating curve (Eq. 4.1). Although the curve refers only to Woodstock, it was applied to the routed flow at the other gauging stations. Since the curve concerns total runoff the actual baseflow was added to the routed surface runoff to give "routed" total runoff.

The sensitivity analyses took no account of the present land use, i.e. no consideration was given to whether the treatment regions could be subjected to the treatment simulated. The main intention with the analyses was to show the flexibility and some potential uses of the technique.

5.7 STATISTICAL ANALYSIS OF THE LOSS RATE

5.7.1 General

To obtain specific answers from the sensitivity analyses involving afforestation, a relationship between the loss rate and the percentage of a catchment in exotic forest was sought by multiple linear regression analysis (Drapter and Smith, 1966).

Twenty variables, representing storm characteristics and catchment conditions, were considered for the regression analysis. However, the variables were screened prior to the analysis and only a representative number of them were finally used. The purpose of the screening was to minimise multicollinearity, by identifying which variables were closely related, and to determine the most useful variables for the regression equation. Multicollinearity is the correlation between independent variables in the regression equation. It produces unstable regression coefficients for the correlated independent variables, and thus obscures the relative importance of these variables in the regression equation.

5.7.2 Principal Components Analysis

One of the methods used in the screening of the variables was principal components analysis, which has been described by Cattell (1965) and applied by Anderson (1967, 1970) and Rice (1970). It is a statistical technique that can give an insight into the inter-relationships of a large number of variables. The most common way of gaining such an insight is by examining the correlation coefficients between the variables. Principal components analysis improves on this method by reducing the dimensionality of the problem.

It starts with the matrix of correlation coefficients for the variables and linearly transforms the data into a set of uncorrelated column vectors or principal components. The maximum number of components is equal to the number of variables, though often the number of useful components is less than half this figure. The proportion of the variance in the correlation matrix explained by each principal component is additive, with each new component yielded from the analysis explaining less of the variance than the preceding one.

The principal components are related to the original variables via a principal components loading matrix. In the matrix each component contains a number or so-called loading for each variable. The loading gives the correlation of the variable with the component. High loadings in a component indicate that the corresponding variables are closely related and have similar attributes.

Each component is identified by the variables which have high loadings within it. To facilitate the identification of the components the principal components loading matrix is usually rotated by the Varimax criteria (Kaiser, 1958). The rotation tends to eliminate the medium loadings and accentuate the high and low loadings, thereby simplifying the decision as to which variables are important in each component.

In essence, principal components analysis groups variables together which have similar properties as exhibited in the data. The loadings identify which variables are closely related in each component and provide a basis for determining which variable best represents each component or group of variables.

5.8 SUMMARY

The analytical operations of this investigation can now be summarised.

(a) The hydrological data on the sixteen Motueka storms were processed as described in Sections 5.1-5.3, with the discharges and rainfall intensities being determined on an hourly basis.

(b) Lag-mean discharge relationships were sought for the true catchments to obtain initial estimates of A and B for the constituent models.

(c) The Motueka model was tested on four of the sixteen storms; the four storms used had markedly different rainfall characteristics.

(d) Two types of sensitivity analysis were performed (Section 5.4); one type was based on vegetal land treatment, the other on mechanical land treatment. Each analysis that was made compared the effects of equal upstream and downstream treatment on the surface runoff peak and the quantity of suspended sediment transported over the period of surface runoff.

(e) From the data on the sixteen Motueka storms a regression analysis was made of the loss rate on storm and catchment variables. One of the latter variables was the percentage of a catchment in exotic forest.

The results of these operations are contained in Chapter 6.

A number of computer programs were written to facilitate many of the above operations. The development of the programs was a major and integral part of this investigation. Because of their length the programs are not included in this text, but they are briefly described in Appendix C

CHAPTER 6

RESULTS

The Motueka model performed well in reproducing the surface runoff hydrographs of the four test storms (Section 6.2). This was so even though satisfactory lag-mean discharge relationships could not be found for the Motueka catchments (Section 6.1). Subsequent sensitivity analysis demonstrations (Section 6.3) showed the upstream regions of the catchments examined to be more hydrologically sensitive to land treatments than their downstream counterparts, under typical storm conditions.

A multiple linear regression equation was obtained (Section 6.4) in which the loss rate is related to storm variables and the percentage of a catchment in exotic forest. In an illustration of a use of this type of equation the results of some sensitivity analyses are quantified (Section 6.4.8).

6.1 INITIAL ESTIMATES OF A AND B

Using the catchment lag (L) and mean discharge ($\bar{q}_{TS}$) values derived from the sixteen Motueka storms (see Appendix D, Figure D1), a regression analysis of lag on mean discharge was carried out for each true catchment. The intention was to derive relationships in the form of Equation 3.7 and so obtain initial estimates of A and B for each constituent model.

The results of the regressions are given in Table 6.1. They indicate that, for the storms considered, the catchment lag in a true catchment was only weakly related to mean discharge, if at all. The best result was obtained for the smallest catchment, the Upper Motueka. The size of the regression data sample for this catchment, necessitated by two "negative" loss rates (Section 6.4.2), was coincidental.

TABLE 6.1

CORRELATIONS OF CATCHMENT LAG WITH MEAN DISCHARGE

Catchment	No. of Storms	Equation	Correlation Coefficient r	Standard Error of Estimate, hrs
Upper Motueka	14	$L = 29.1\bar{q}_{TS}^{-0.146}$	-0.575	1.22
Wangapeka	16	$L = 14.4\bar{q}_{TS}^{-0.015}$	-0.041	1.24
Baton	16	$L = 35.1\bar{q}_{TS}^{-0.165}$	-0.425	1.23
Woodstock	16	$L = 10.4\bar{q}_{TS}^{+0.047}$	+0.171	1.20
Motueka	16	$L = 15.3\bar{q}_{TS}^{+0.024}$	+0.107	1.17

Because of these poor correlations between lag and mean discharge, initial estimates of A and B for the Upper Motueka, Wangapeka and Baton models were obtained instead from Askew's lag-topographical relationship (Eq. 3.5). Substitution in Equation 3.5 for the three upstream catchments gave

$$L = 63.2\bar{q}_{TD}^{-0.230} \quad \text{(Upper Motueka)} \qquad \ldots\ldots\ldots\ldots 6.1$$

$$L = 94.1\bar{q}_{TD}^{-0.230} \quad \text{(Wangapeka)} \qquad \ldots\ldots\ldots\ldots 6.2$$

$$L = 65.6\bar{q}_{TD}^{-0.230} \quad \text{(Baton)} \qquad \ldots\ldots\ldots\ldots 6.3$$

Although Equations 6.1-6.3 refer to direct runoff it was assumed they could also be used for surface runoff. This assumption was considered reasonable; the distinction between the two forms of runoff is arbitrary and the characteristics of each are very similar. It will be observed that the coefficients (A) and the absolute exponent values (B) in Equations 6.1-6.3 differ noticeably from the values in the corresponding equations in Table 6.1.

Equation 3.5 was not used to obtain initial estimates of A and B for the Minor Woodstock and Minor Motueka models - the areas of the Woodstock and Motueka catchments being far greater than the upper limit of 50 square miles (130 km^2) recommended for Equation 3.5. (The true catchment areas were considered in connection with Equation 3.5 rather than the minor catchment areas in recognition of the effect on the flow, and therefore on A and B, of the catchment area upstream of a minor catchment.) The initial estimates for the two minor models were arrived at by regressing catchment lag on mean discharge for the Woodstock and Motueka catchments, considering only five out of the total of sixteen storms. These five storms were the ones which occurred in the summer months (see Appendix D, Figure D1, for the storm dates). The coefficient and absolute exponent values of the resulting regression equations (given in Table 6.2) were taken as the initial A and B values.

The ordinary mean discharge $\bar{q}_T$ was used in obtaining the equations in Table 6.2 rather than the weighted form $\bar{q}_{TS}$, since of the two parameters it was the one more closely correlated (by approximately 20 percent on average) with catchment lag. (With the equations in Table 6.1 the difference between using $\bar{q}_{TS}$ and $\bar{q}_T$ was minimal.)

TABLE 6.2

CORRELATION OF CATCHMENT LAG WITH MEAN DISCHARGE
CONSIDERING ONLY THE FIVE SUMMER STORMS

Catchment	Equation	Correlation Coefficient, r	Standard Error of Estimate, in hours
Woodstock	$L = 128\bar{q}_T^{-0.241}$	-0.82	1.06
Motueka	$L = 189\bar{q}_T^{-0.270}$	-0.91	1.07

Even allowing for the fact that only five storms were involved, the results in Table 6.2 suggest that for the summer storms there is a rather definite inverse relationship between lag and mean discharge in the Woodstock and the Motueka catchments. The contrast between these results and the corresponding ones in Table 6.1 indicates that storms should be considered on a seasonal basis for the two catchments if satisfactory lag-mean discharge relationships are to be obtained. It is interesting to note that the exponents in the equations in Table 6.2 are in close agreement with the exponent of -0.230 in Askew's lag-topographic relationship (Eq. 3.5).

6.2 RUNOFF ROUTING WITH THE MOTUEKA MODEL

6.2.1 Equation 3.5 Suitable for New Zealand Catchments?

Askew (1968a,b) derived Equation 3.5 so that A and B could be determined for a Laurenson model of an ungauged catchment. The fact that Equation 3.5 was used to determine the initial A and B values for the models of the three upstream catchments provided an opportunity of examining whether the equation was suited to New Zealand conditions.

A preliminary examination was made by applying the Upper Motueka, Wangapeka and Baton models to storm no. 6 (documented in Appendix D) and using the appropriate A and B values in Equations 6.1-6.3, but initially without optimisation to these values. The resulting routed surface runoff hydrographs (Figure 6.1) were too attenuated and delayed. Optimisation of the A and B values considerably improved the reproductions, as shown in Figure 6.2 and confirmed by Table 6.3, which compares the goodness-of-fit of the initial and optimum routed hydrographs.

6.2.2 Motueka Model Tests

The Motueka model was tested on storms no. 6, 13, 21 and 24, which are documented in Appendix D. The testing produced twenty optimum routed surface runoff hydrographs, i.e. one at each gauging station for each storm. The hydrographs are shown in Figure 6.2 (already referred to in Section 6.2.1) and Figures 6.3-6.9, while their goodness-of-fit is summarised in Appendix D, Figure D10.

The performance of the Motueka model in these tests is evaluated and discussed in Section 7.1.

The initial estimates of A and B described in Section 6.1 were only used in the model for storm no. 6. For the tests on the remaining storms it was more practical and economic to use initial A and B values the same or almost the same as the optimum values found in a preceding test. The optimum A and B values obtained for each storm and constituent model are included in Figure D10 in Appendix D.

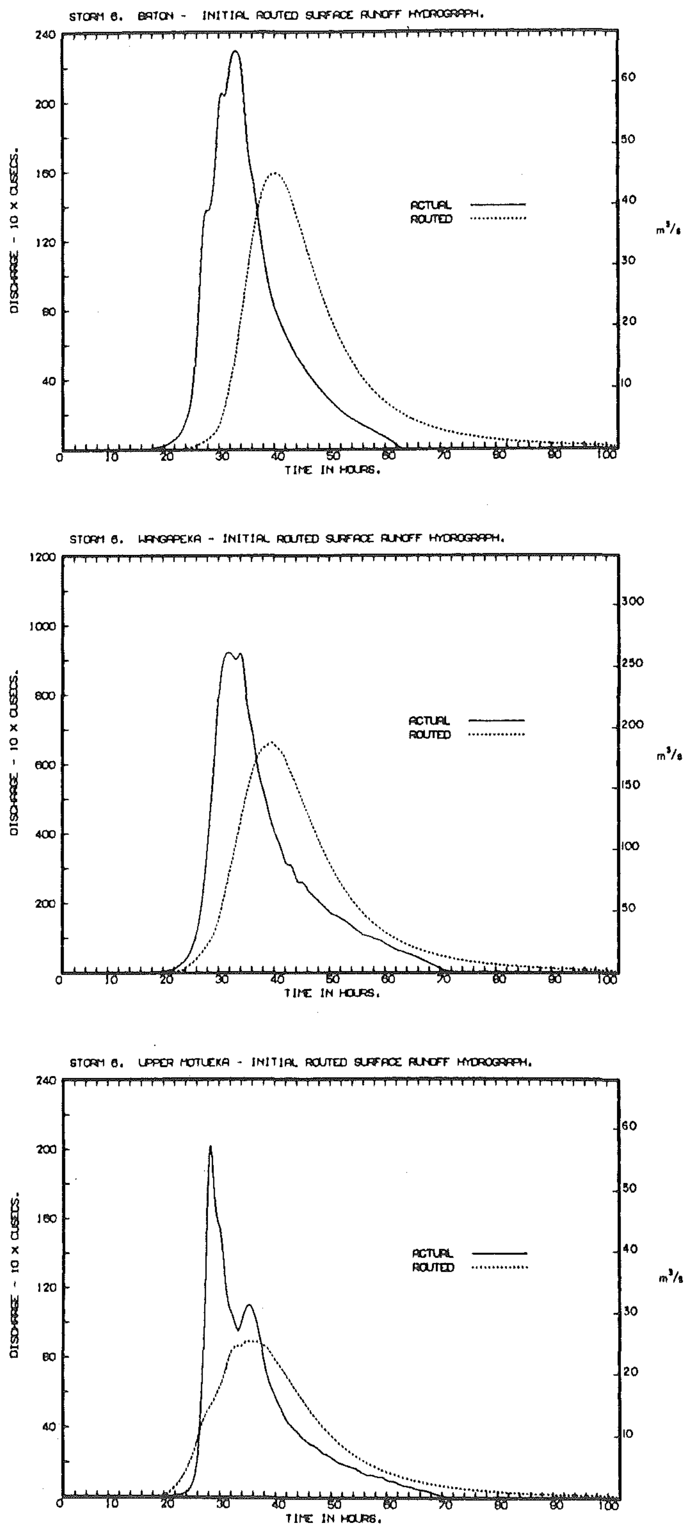


FIG. 6.1: STORM NO.6 - ROUTED HYDROGRAPHS USING EQUATION 3.5

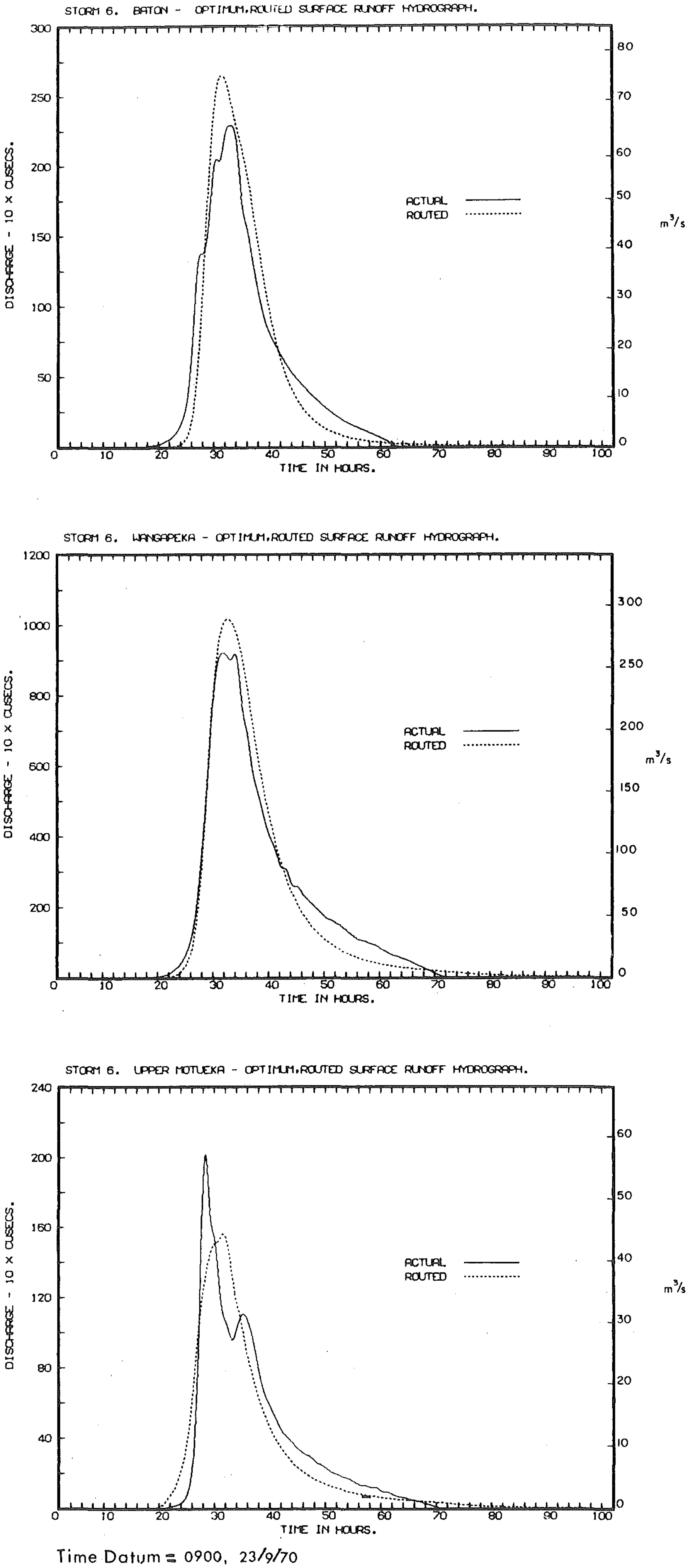


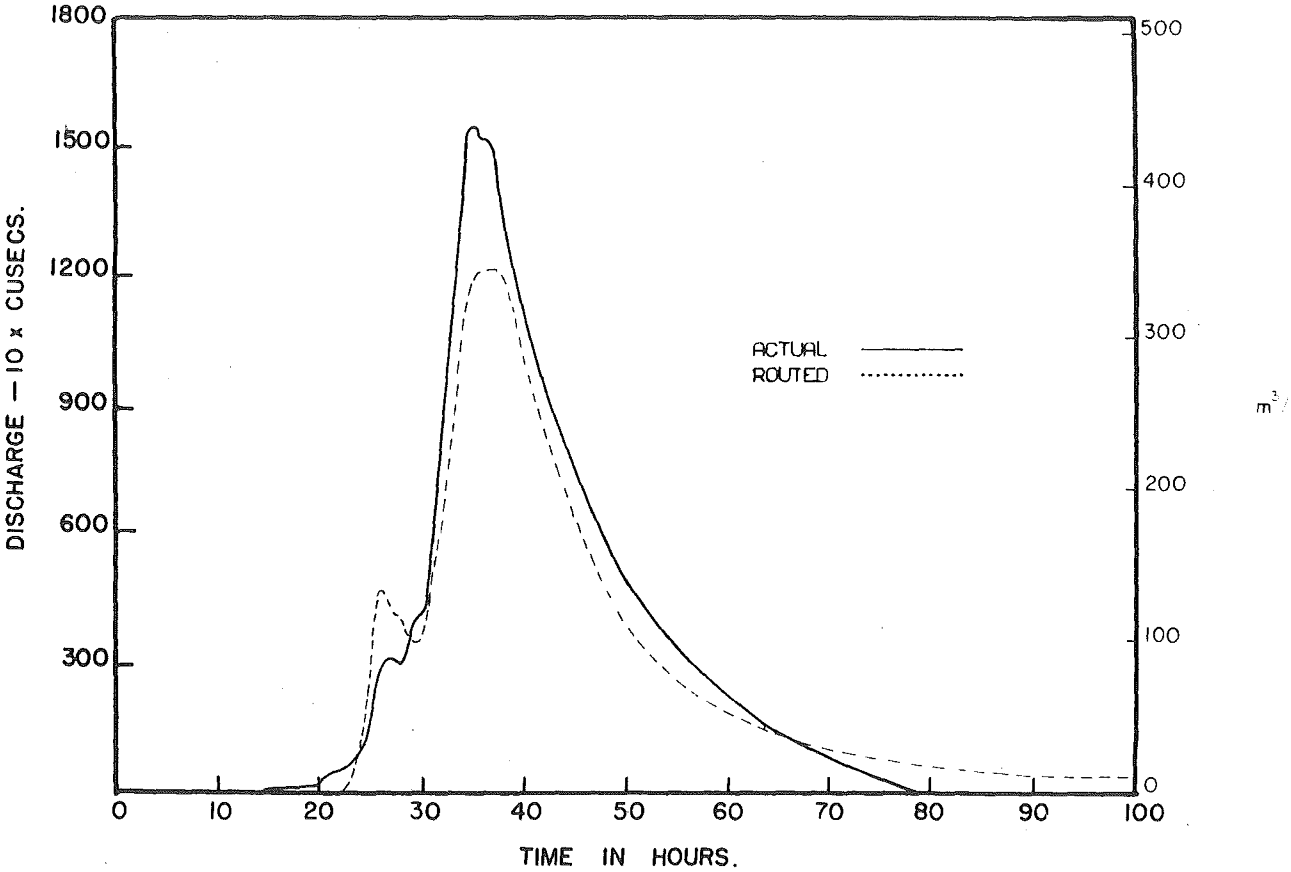
FIG. 6.2 : STORM NO. 6 - OPTIMUM ROUTED HYDROGRAPHS

TABLE 6.3

DETAILS OF THE INITIAL AND OPTIMUM ROUTED SURFACE RUNOFF HYDROGRAPHS IN FIGURES 6.1 AND 6.2

	Upper Motueka Model		Wangapeka Model		Baton Model	
	Initial	Optimum	Initial	Optimum	Initial	Optimum
Model Efficiency	0.549	0.876	0.250	0.955	-0.455	0.875
Integral Square Error	10.6%	5.56%	12.6%	3.08%	17.9%	5.30%
"Correlation Coefficient"	0.886	0.965	0.782	0.988	0.565	0.969
Coefficient of Variation	0.563	0.393	0.807	0.220	1.28	0.340
Variation in S.R. Peak	-54.4%	-20.6%	-27.9%	+11.6%	-31.2%	+15.1%
Coefficient, A	63.2	126.5	94.1	145.6	65.6	33.7
Exponent, B	0.230	0.4381	0.230	0.3447	0.230	0.235

STORM 6. AT BLUEGUM CORNER — OPTIMUM ROUTED SURFACE RUNOFF HYDROGRAPH.



STORM 6. AT WOODSTOCK - OPTIMUM ROUTED SURFACE RUNOFF HYDROGRAPH.

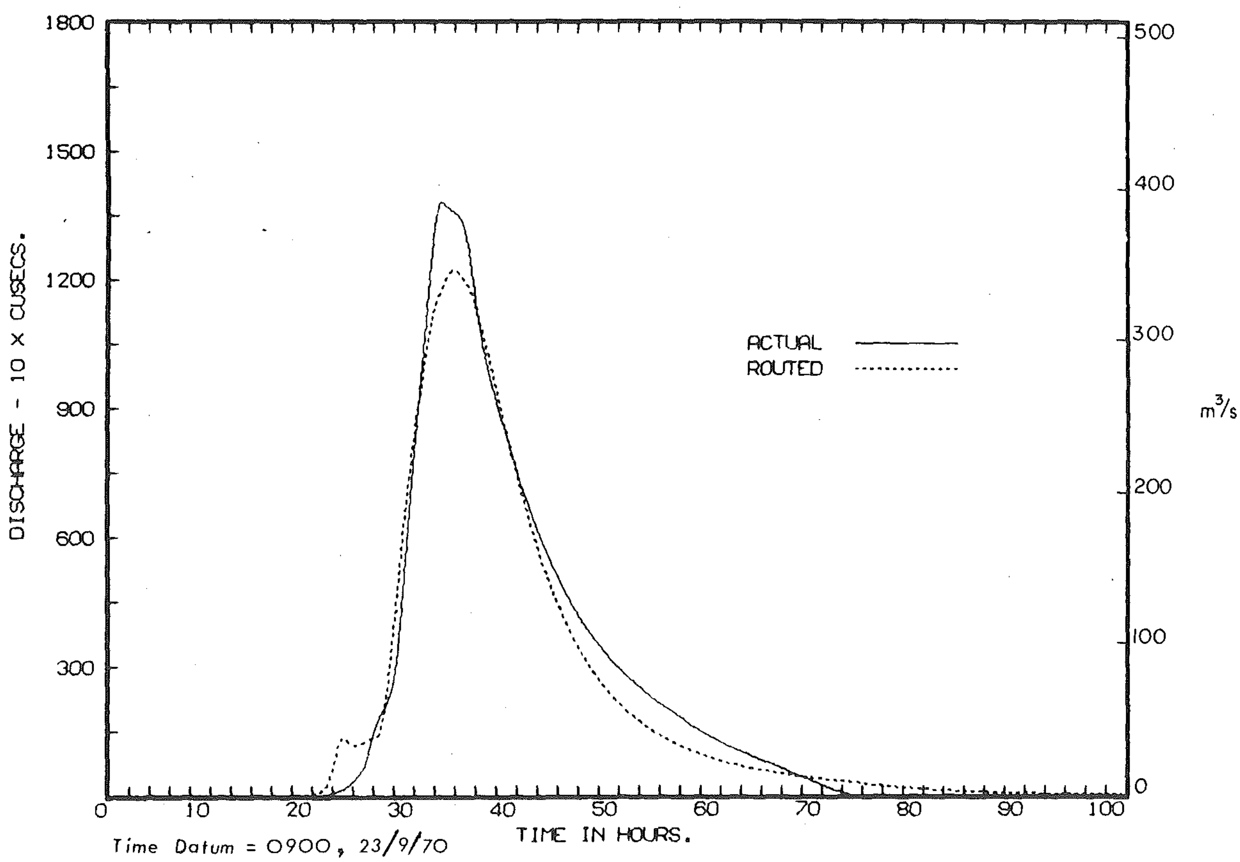


FIG. 6.3 : STORM NO. 6 - OPTIMUM ROUTED HYDROGRAPHS

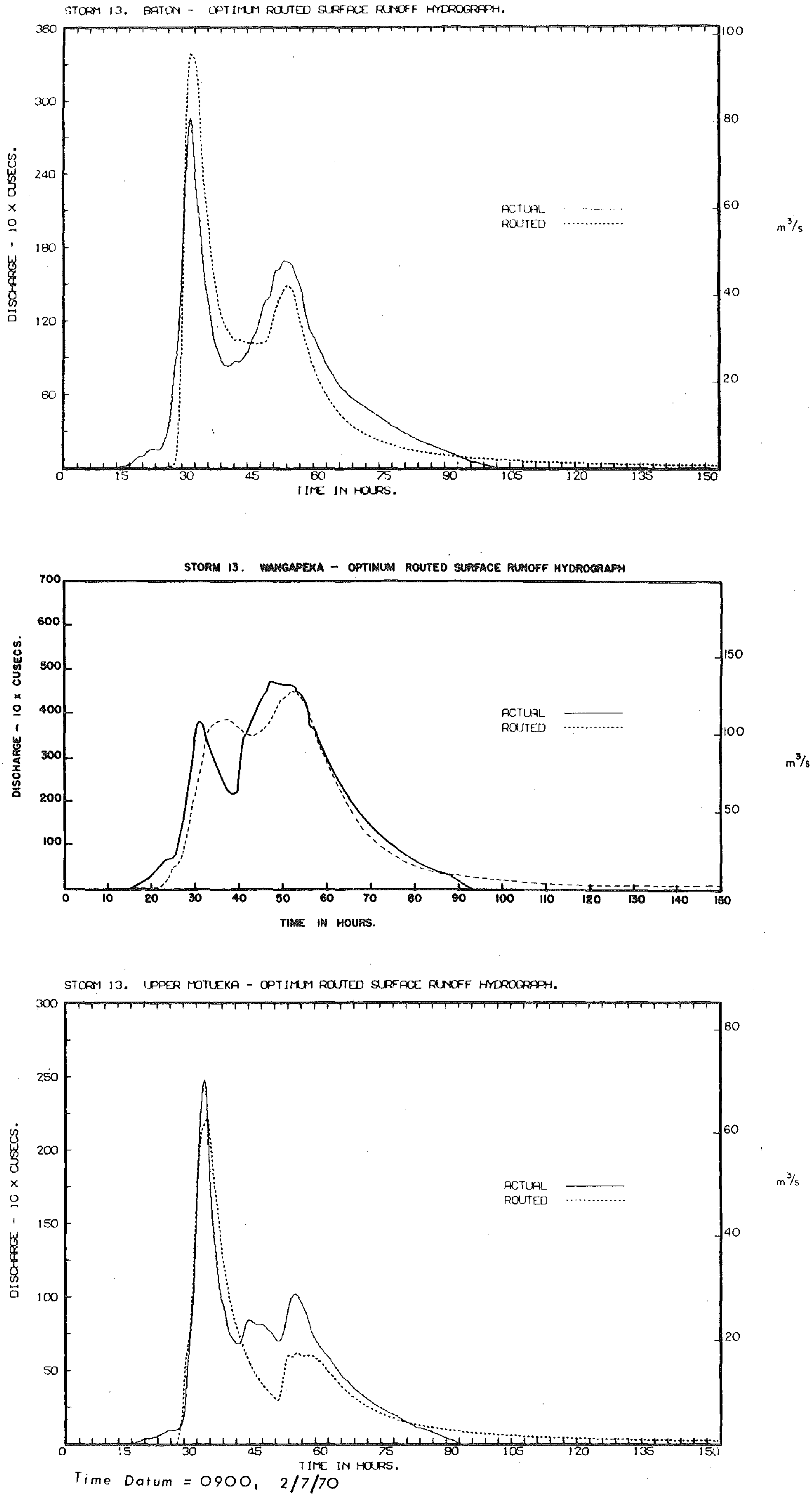
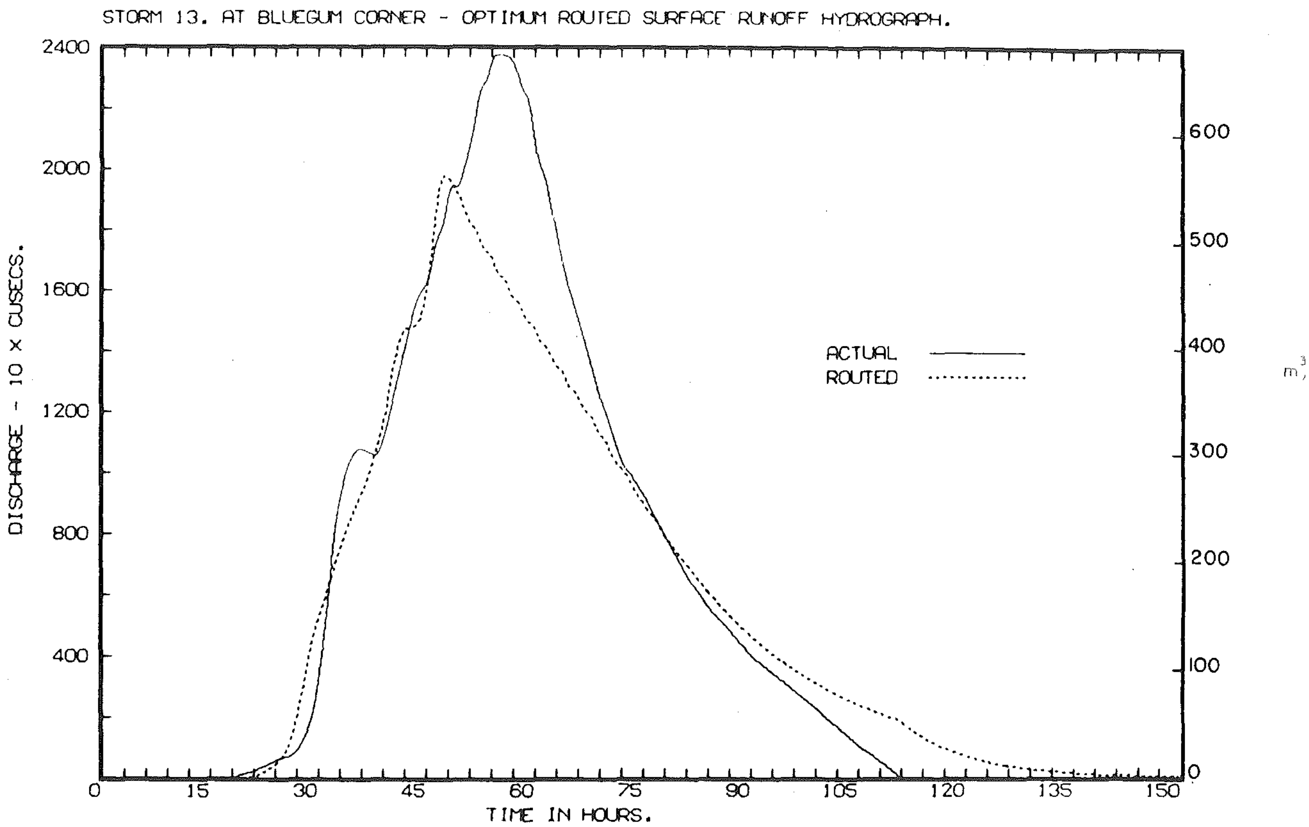


FIG. 6.4 : STORM NO. 13 - OPTIMUM ROUTED HYDROGRAPHS



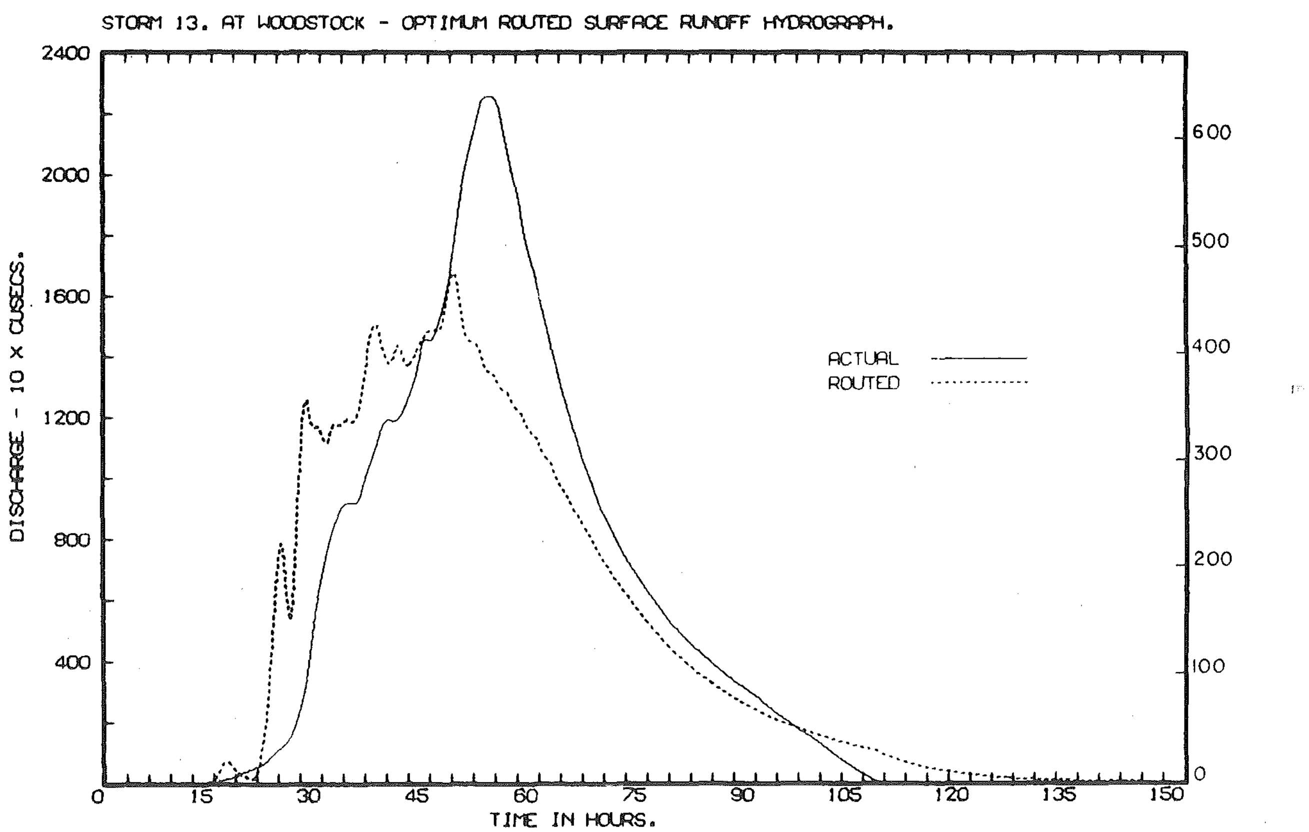
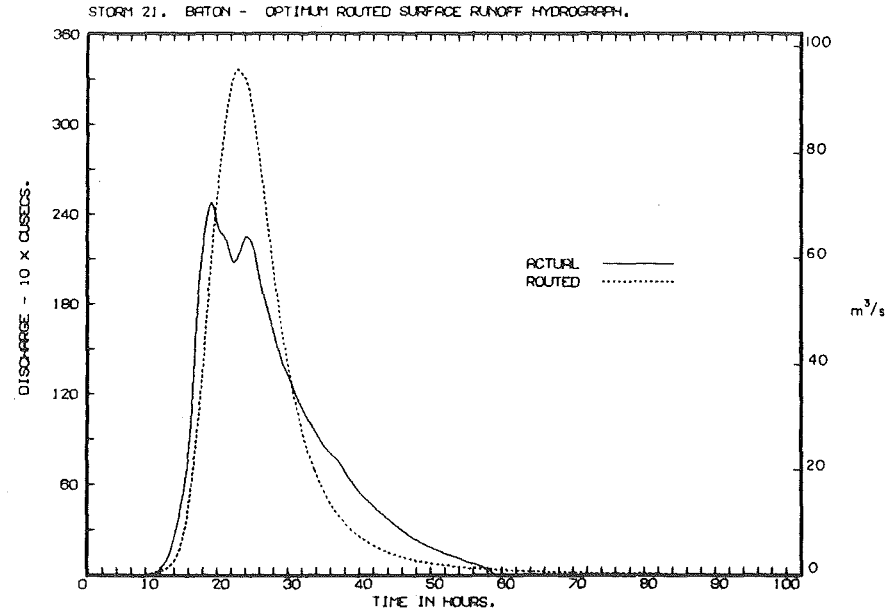
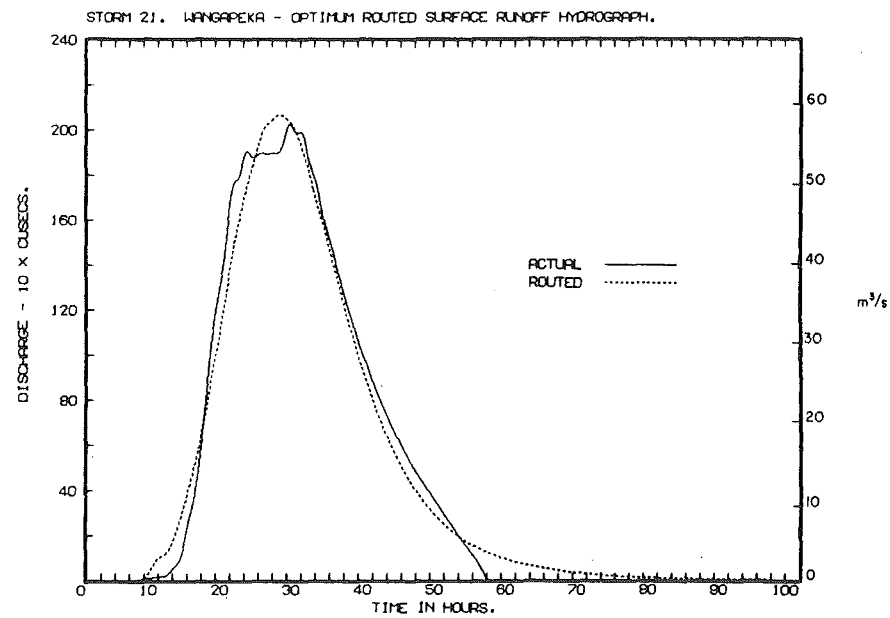
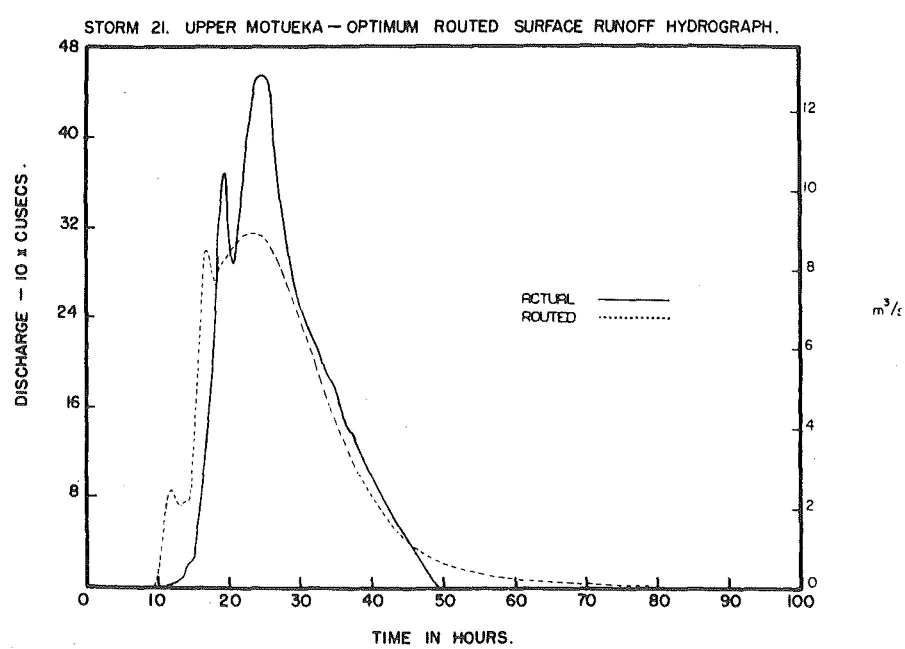


FIG. 6.5: STORM NO.13 - OPTIMUM ROUTED HYDROGRAPHS

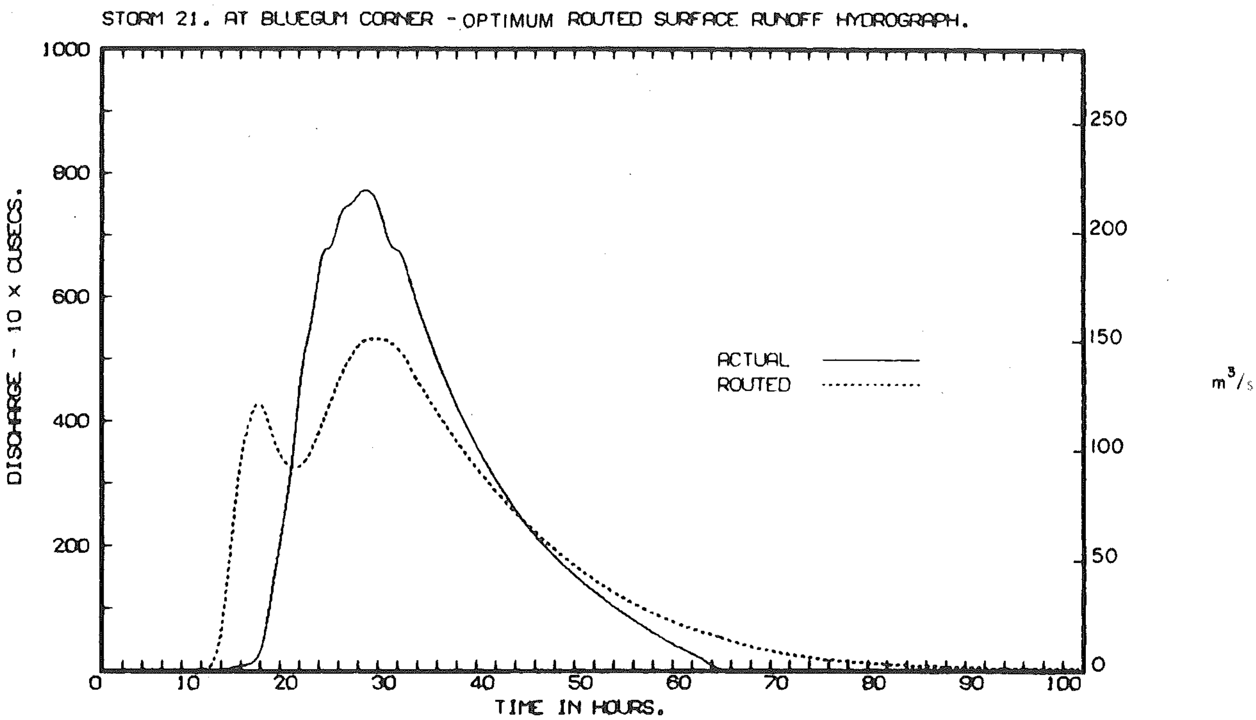






Time Datum = 0900, 24/9/69

FIG. 6.6: STORM NO.21 - OPTIMUM ROUTED HYDROGRAPHS



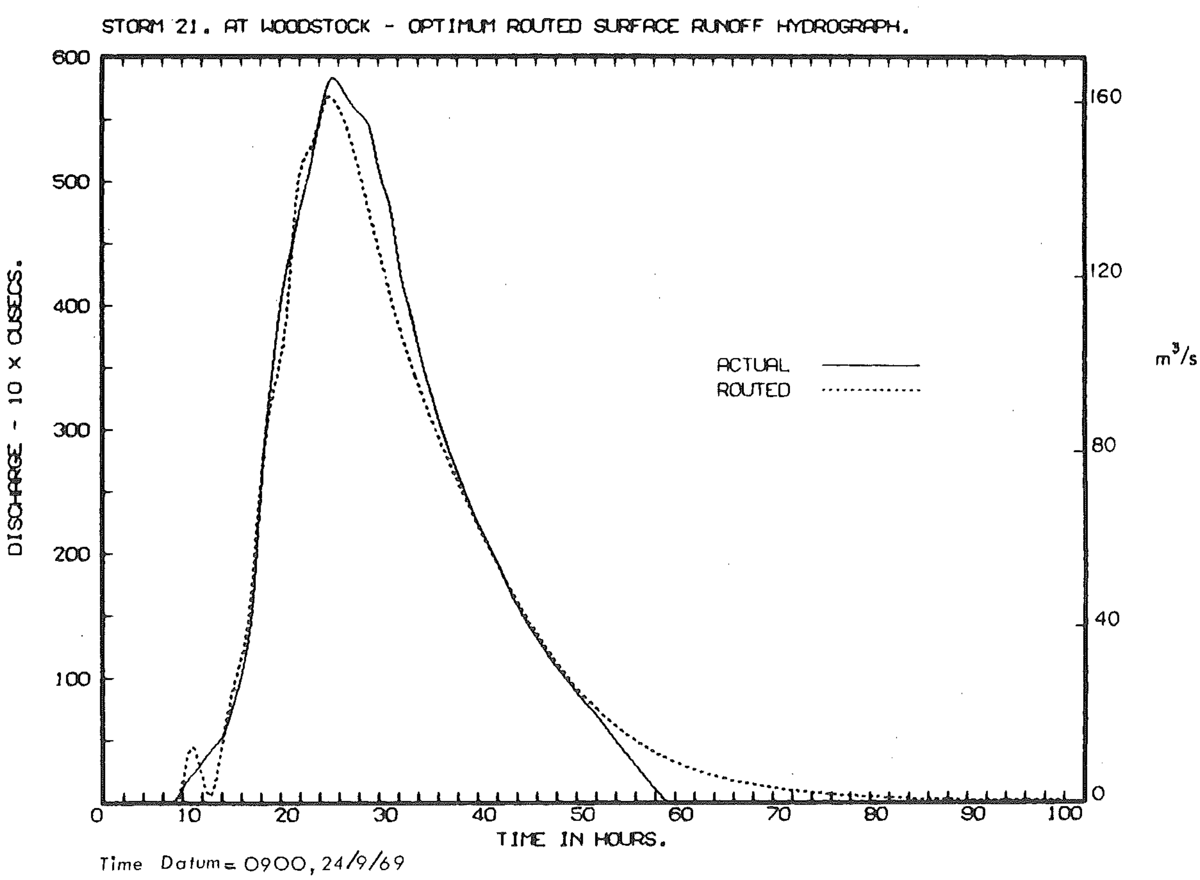


FIG. 6.7: STORM NO.21 - OPTIMUM ROUTED HYDROGRAPHS

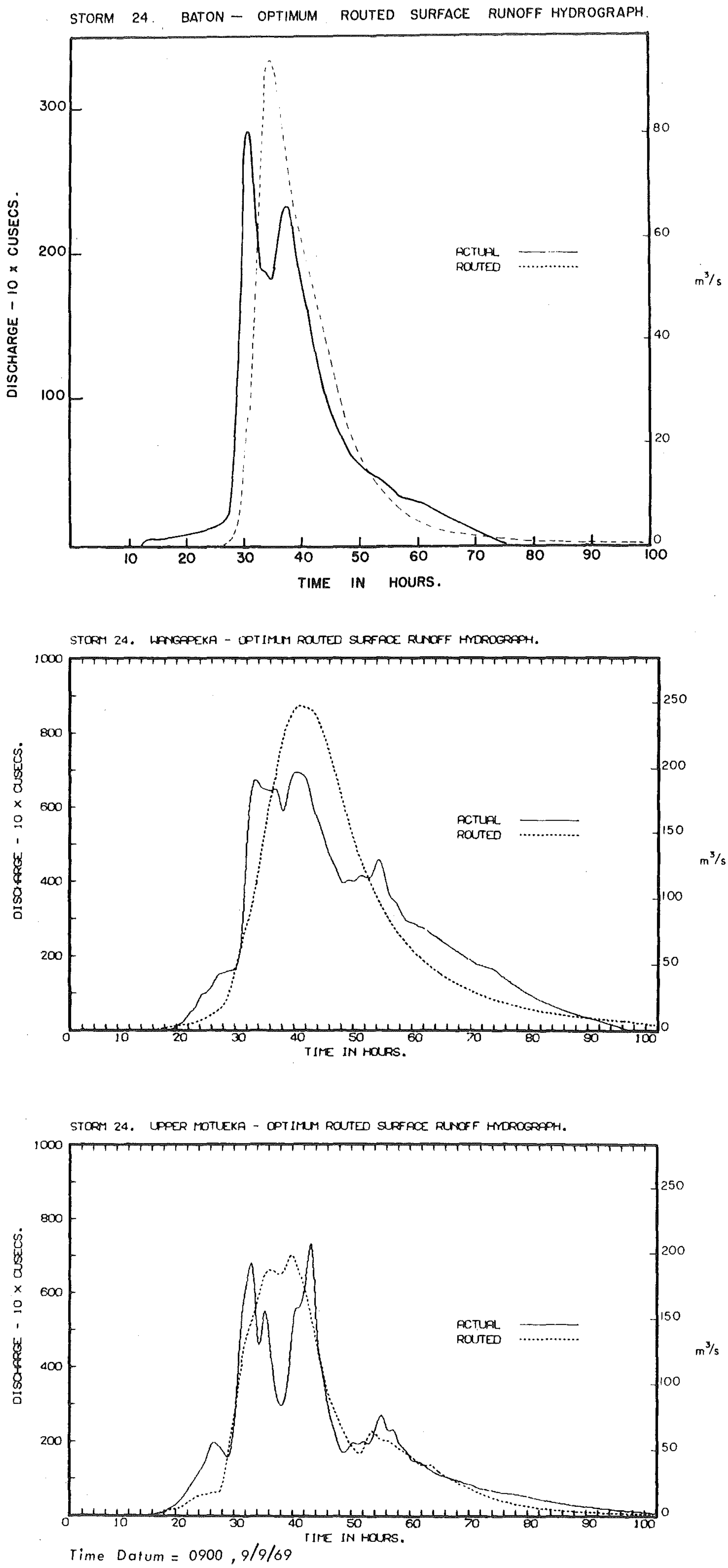
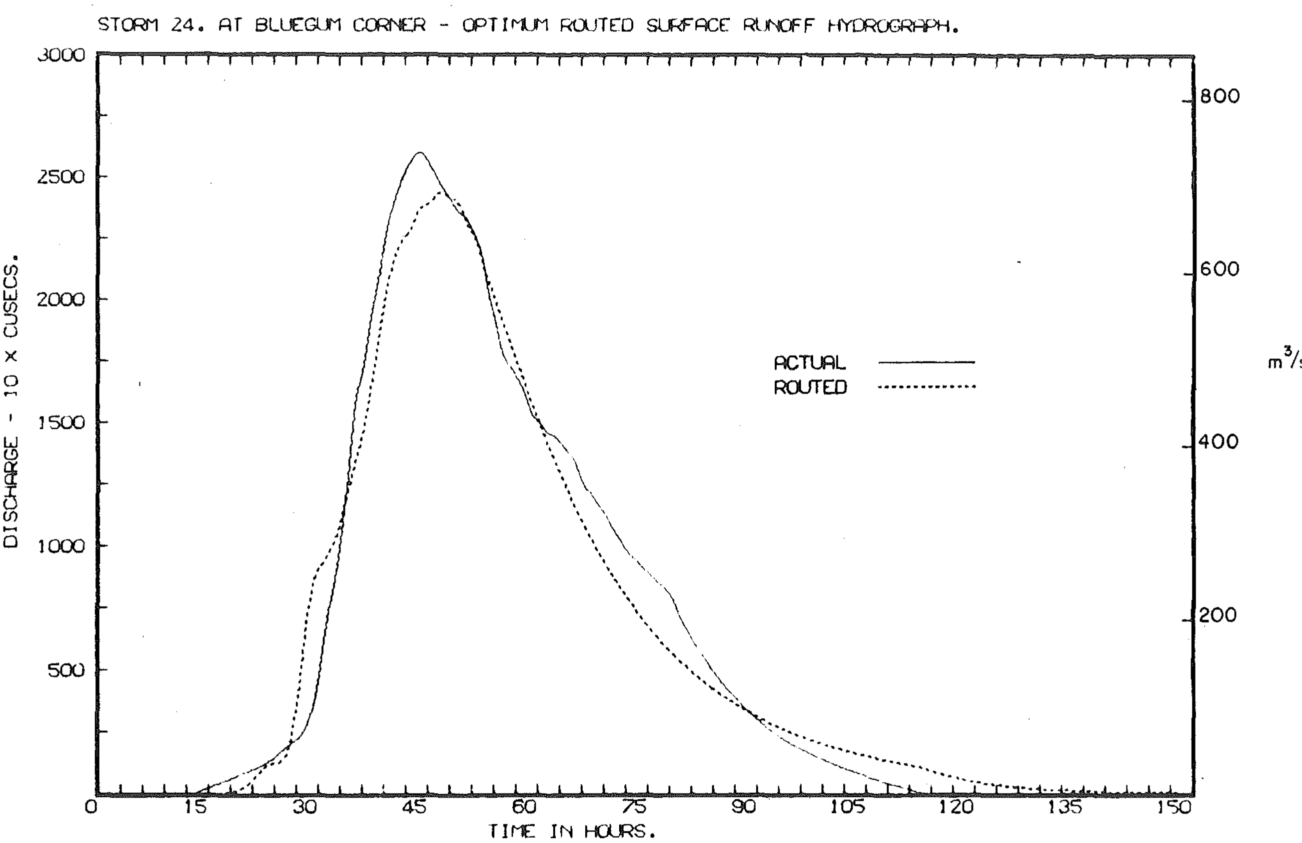


FIG. 6.8: STORM NO.24 - OPTIMUM ROUTED HYDROGRAPHS



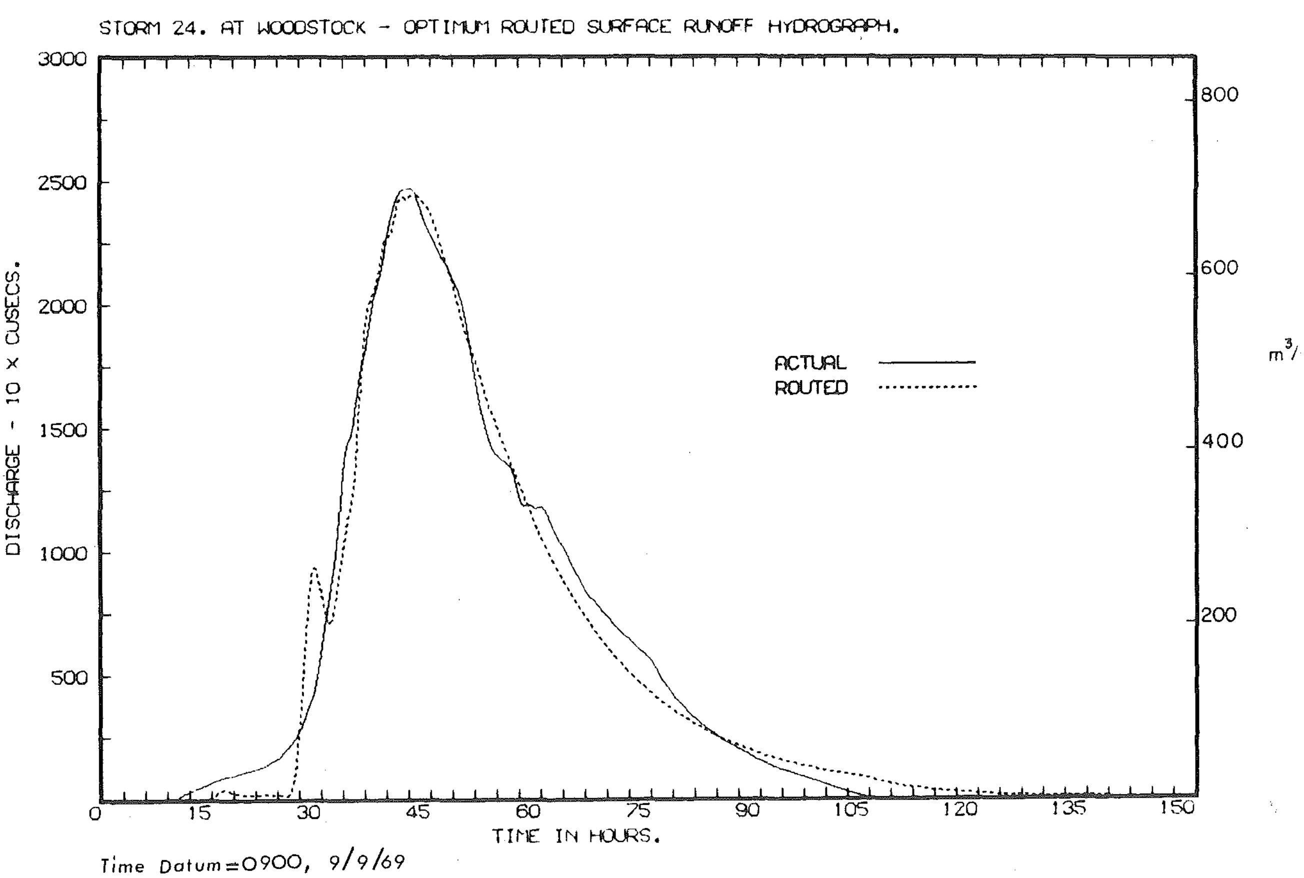


FIG. 6.9 : STORM NO. 24 - OPTIMUM ROUTED HYDROGRAPHS

6.2.3 Effects of Using Multiple Loss Rates for a Storm

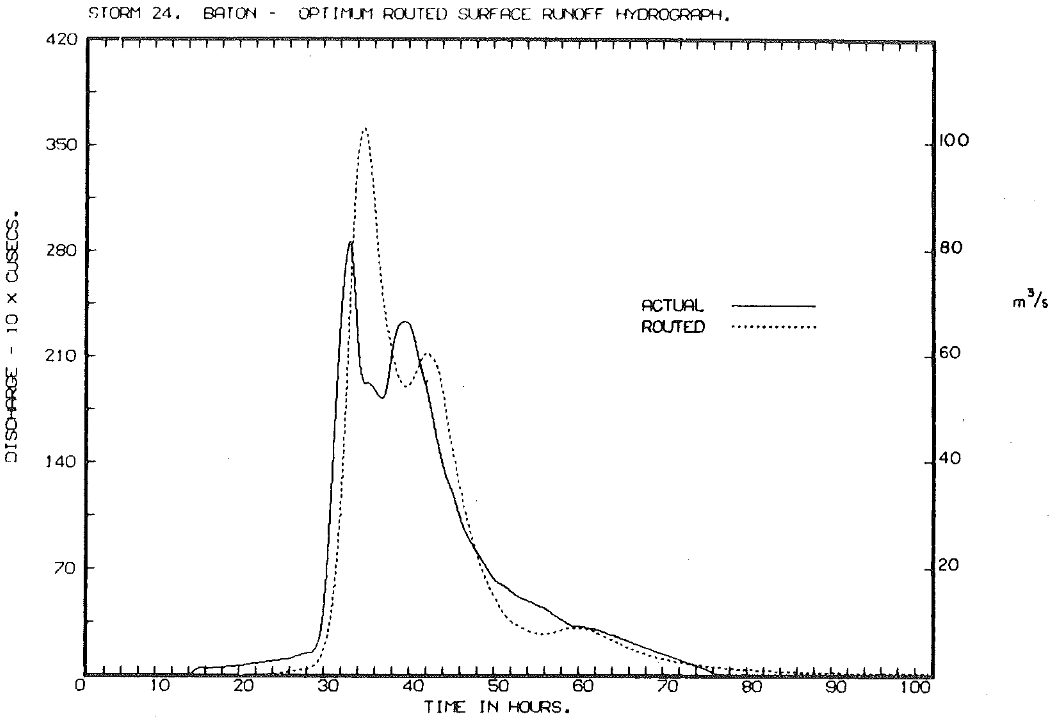
In this investigation only one loss rate was used for each catchment for a storm. However, with the way in which the time limits of a storm were defined (Section 5.2.1) the storm surface runoff hydrograph for an upstream catchment was sometimes multi-peaked, even though the corresponding downstream hydrograph at the outlet of the much larger Motueka catchment was essentially single-peaked. For these multi-peak hydrographs there was the possibility of deriving a loss rate for each corresponding rainfall burst. The effect on the routing results of using a single loss rate for a storm, even though the relevant hydrograph was multi-peaked, was examined with the Baton model and storm no.24.

The multi-peak surface runoff hydrograph at the Baton outlet for storm no.24 was divided into separate rises according to the corresponding rainfall bursts. The isohyetal map for each burst was kept the same as that for the original storm. The resulting routed surface runoff hydrograph from the Baton model was a more realistic reproduction, with the efficiency being increased from 0.510 to 0.729 (see Figure 6.10). This improvement can be attributed entirely to the use of multiples loss rates achieving a better approximation of the infiltration capacity curve.

6.3 SENSITIVITY ANALYSES

6.3.1 General

The sensitivity analyses were performed with test storms for which the relevant models satisfactorily reproduced the surface runoff hydrographs. In the analyses based on vegetal land treatment the Upper Motueka, Wangapeka and Baton models were involved. The storms used were nos. 6 and 13. It was considered (Section 7.1.1) that for these two storms all three models gave satisfactory surface runoff hydrograph reproductions.



Parameter	One Loss Rate (Fig. 6.8)	Four Loss Rates (Figure above)
Coefficient, A	60.0	45.2
Exponent, B	0.281	0.289
Model Efficiency	0.510	0.729
Integral Square Error	0.944%	7.31%
"Correlation Coefficient"	0.877	0.926
Coefficient of Variation	0.661	0.552
Variation in S.R. Peak	14.6%	25.7%

FIG. 6.10: BATON MODEL AND STORM NO.24 - EFFECTS OF USING MULTIPLE LOSS RATES

With the sensitivity analysis based on mechanical land treatment the full Motueka model was involved. Since the model gave an excellent reproduction at Bluegum Corner for storm no.24 (see Figure 6.9 and Section 7.1.1), this storm was used in the analysis.

6.3.2 Vegetal Land Treatment

In the first type of sensitivity analysis, the effects of afforestation were simulated at two different locations in each of the Upper Motueka, Wangapeka and Baton catchments. The treatment regions each covered 25 percent of the catchment area and were located in the upstream (upper) and downstream (lower) parts of the catchments (see Appendix D, Figures D11-D13).

The results of the sensitivity analyses of these three catchments for storm no.6 are summarised by the curves in Figures 6.11-6.13. The curves for each catchment indicate that, for storm no.6, greater reductions in the surface runoff peak and the quantity of suspended sediment would be achieved if the upper region rather than the lower region was afforested.

Just how much greater the reductions would be depends on the actual increase in the loss rate following the afforestation. If, for example, the storm loss rates for the catchments were increased by 100 percent, then the surface runoff peak reductions from afforesting the upper regions of the three catchments would, on average, be more than 50 percent greater than those resulting from similar treatment in the corresponding lower regions.

The same analyses were subsequently carried out for storm no.13. The isohyetal pattern for this storm (see Appendix D, Figure D4) was

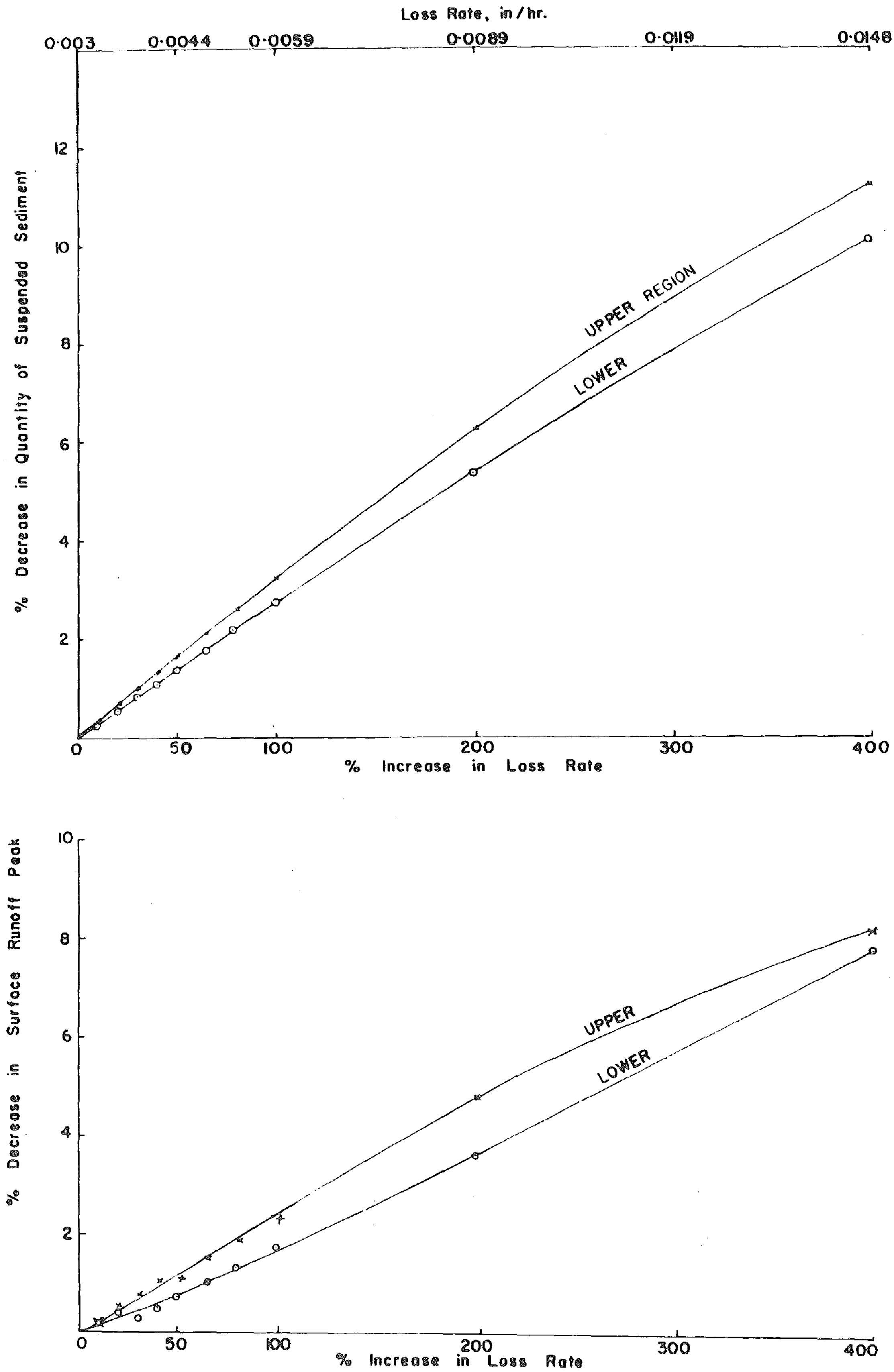


FIG.6.11: STORM NO. 6 - SENSITIVITY ANALYSIS CURVES FOR THE UPPER MOTUEKA CATCHMENT

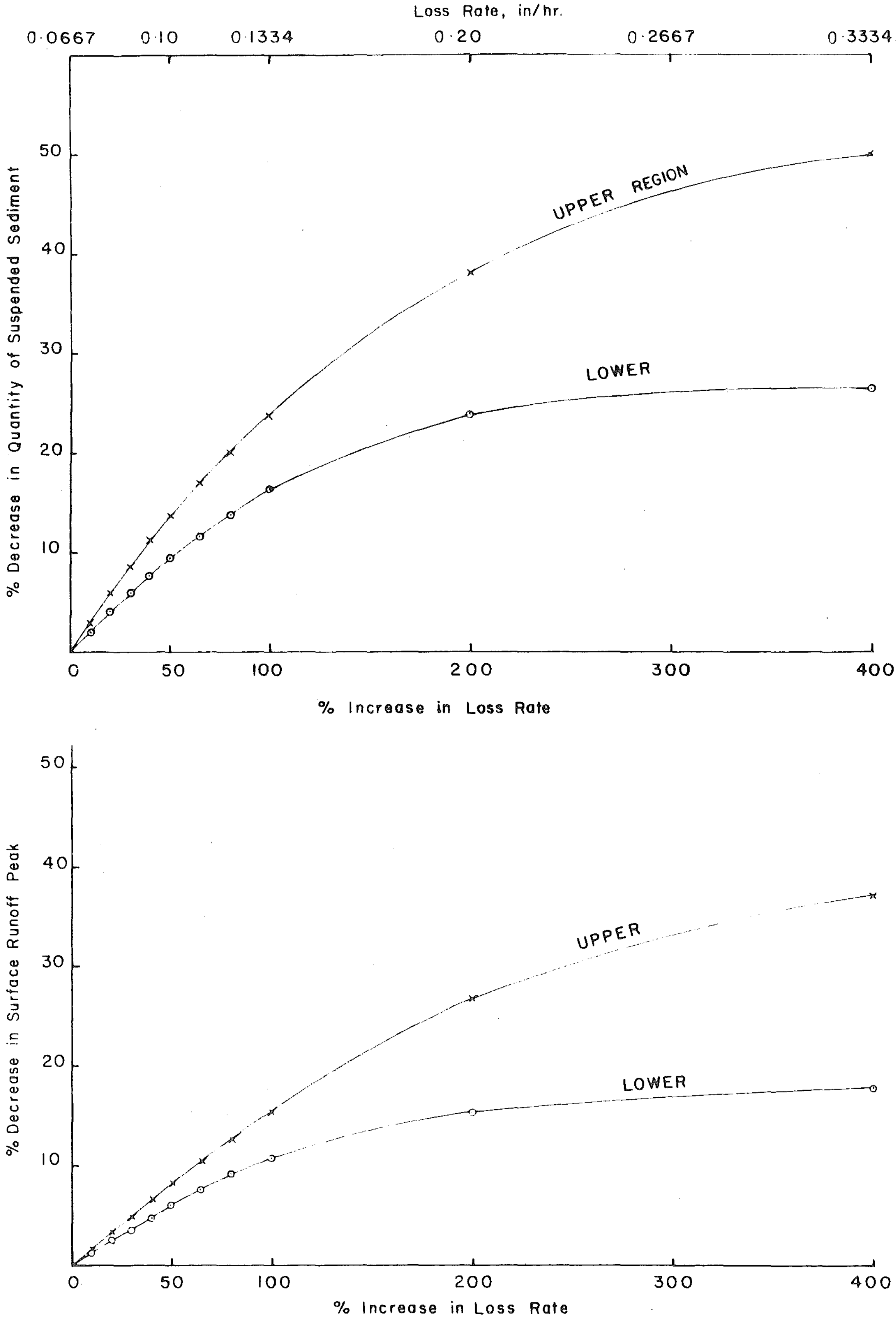


FIG.6.12: STORM NO. 6 - SENSITIVITY ANALYSIS CURVES FOR THE WANGAPEKA CATCHMENT

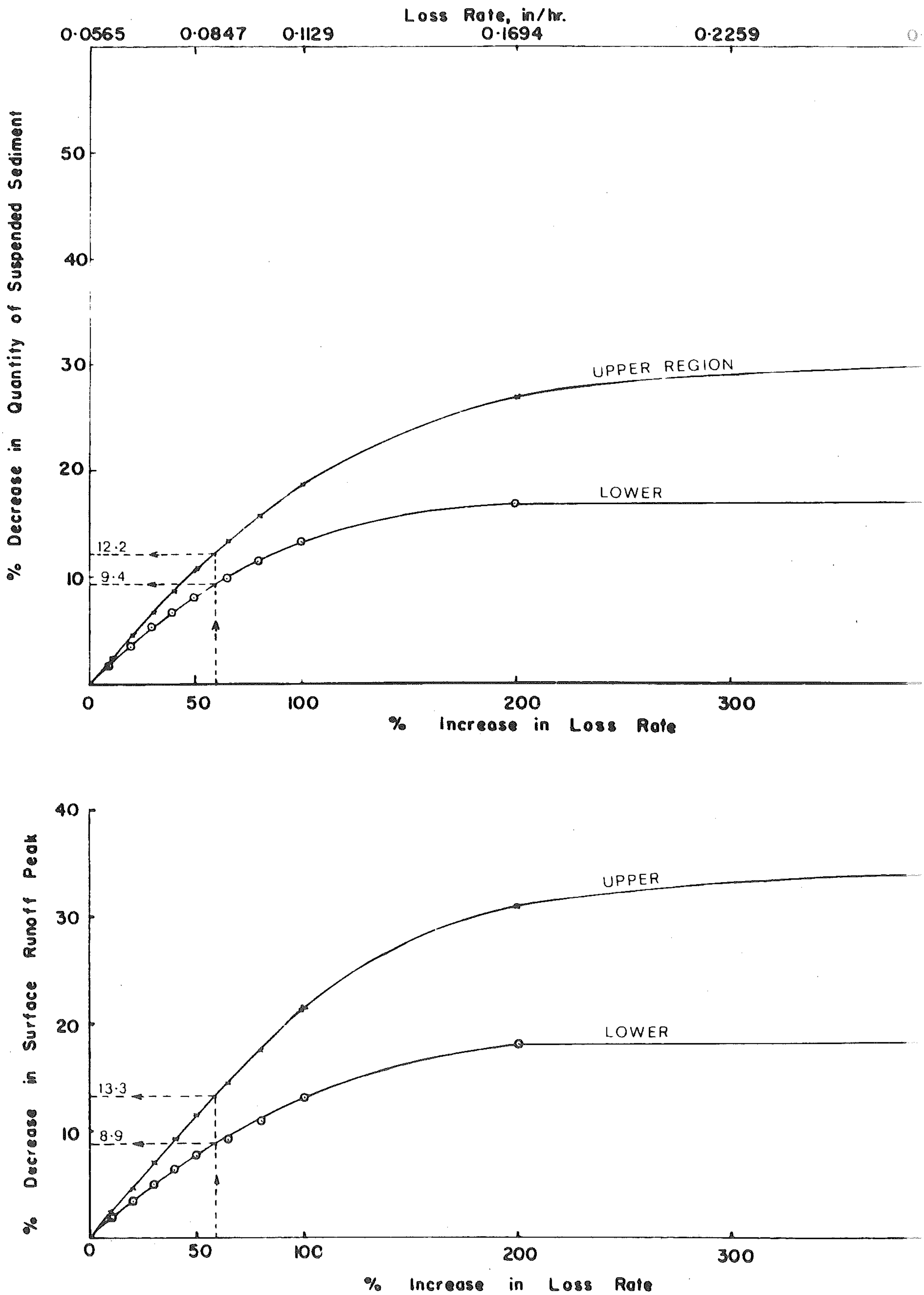


FIG.6.13: STORM NO.6 - SENSITIVITY ANALYSIS CURVES FOR THE BATON CATCHMENT

exceptional; it was a general reversal of the normal situation with the greatest rainfall depths in the Wangapeka and Baton catchments occurring in the lower parts of these catchments. The reversal was reflected in the sensitivity analysis results (Figures 6.14-6.16) - the lower treatment regions in the Wangapeka and Baton catchments exhibiting greater hydrological sensitivity to afforestation than the corresponding upper regions.

6.3.3 Mechanical Land Treatment

In the second type of sensitivity analysis, the effects of a series of diversion or retention dams were simulated in two different locations in the Motueka catchment. The upper treatment region was the whole of the Wangapeka catchment; the lower one was a region of equal area immediately upstream of Bluegum Corner.

The analysis involved the routed surface runoff hydrograph at Bluegum Corner for storm no.24. For this storm the analysis showed (see Table 6.4) the upper treatment region to be the more hydrologically sensitive region to the mechanical land treatment.

TABLE 6.4

SENSITIVITY ANALYSIS RESULTS FOR THE MECHANICAL LAND TREATMENT

	Downstream Treatment	Upstream Treatment
Area of the Motueka catchment involved	17%	17%
Sub-areas involved	Nos.15 (part of), 16,17,18,19,20	No. 2 (i.e. Wangapeka catchment
Decrease in surface runoff peak at Bluegum Corner	4.9%	19.4%
Decrease in the quantity of suspended sediment at Bluegum Corner	27.8%	38.0%

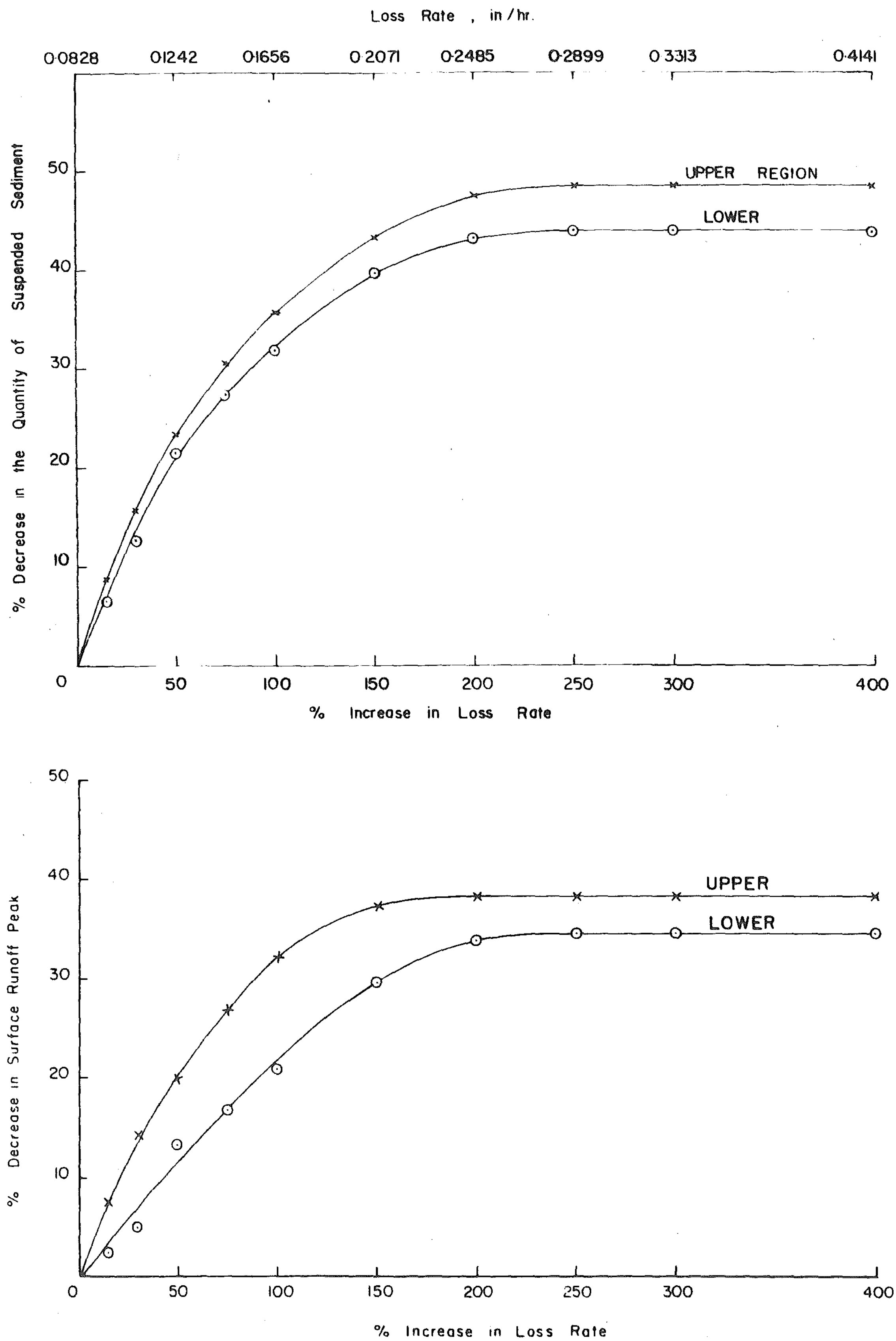


FIG. 6.14: STORM NO.13 - SENSITIVITY ANALYSIS CURVES FOR THE UPPER MOTUEKA CATCHMENT

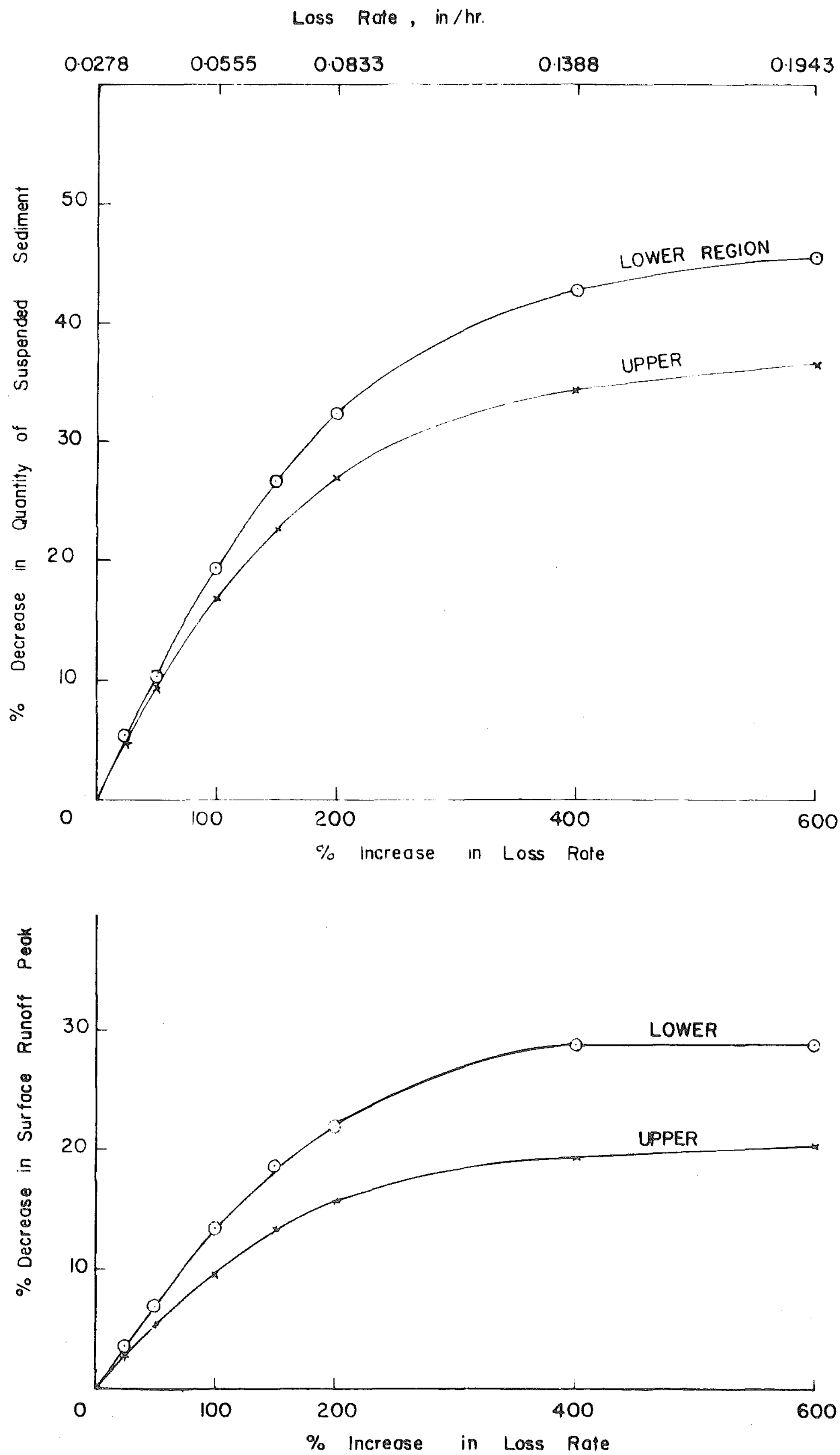


FIG. 6.15; STORM NO.13 - SENSITIVITY ANALYSIS CURVES FOR THE WANGAPEKA CATCHMENT

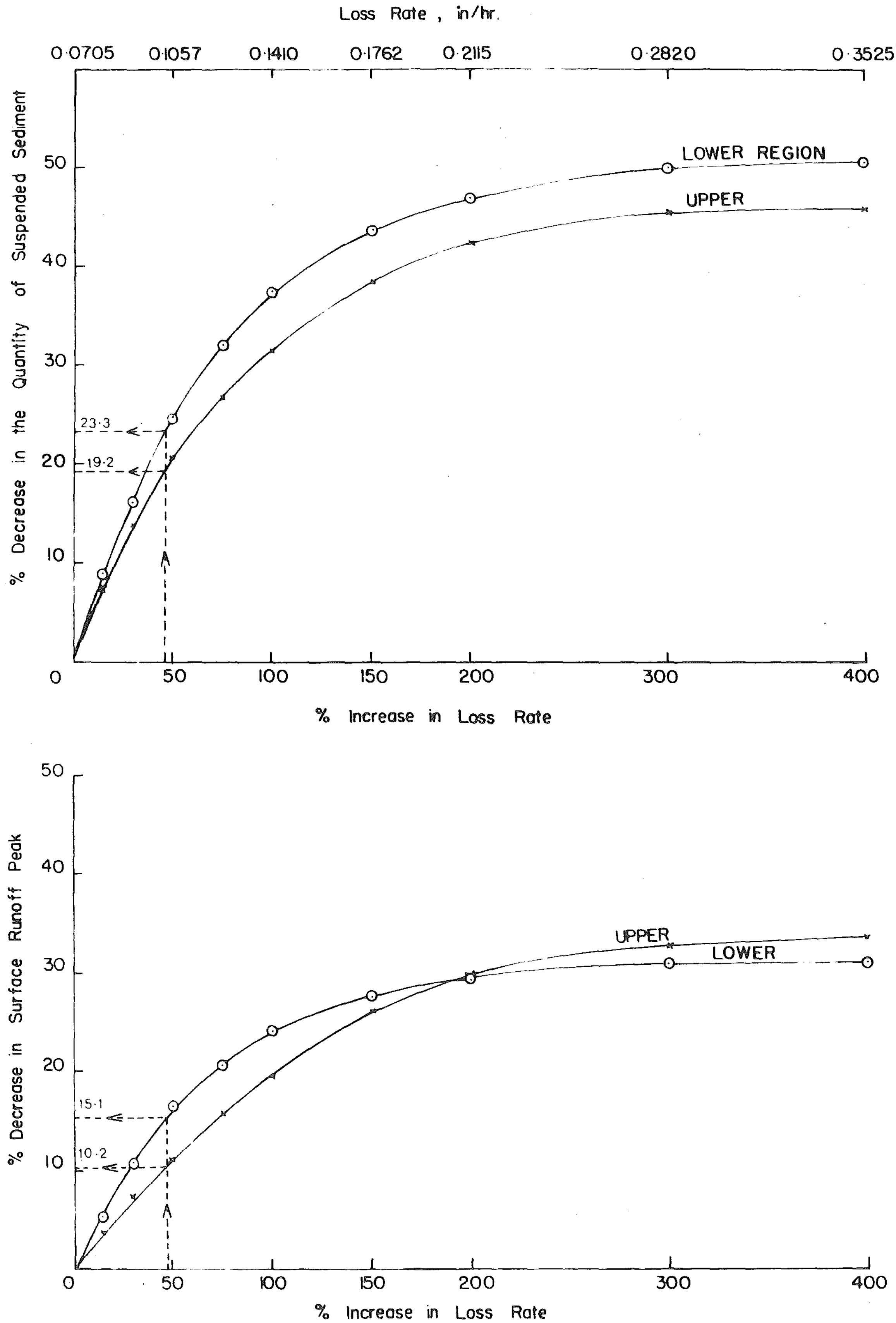


FIG. 6.16: STORM NO.13 - SENSITIVITY ANALYSIS CURVES FOR THE BATON CATCHMENT

6.4 LOSS RATE REGRESSION ANALYSIS

6.4.1 General

As explained in Section 5.7.1, before a multiple regression analysis was performed to relate the loss rate with the percentage of a catchment in exotic forest, the independent variables considered for the analysis were screened. The screening involved categorising the variables with similar properties. This was done by:

(a) considering the physical relationships of the variables and their effects on the loss rate;

(b) examining the correlation coefficients between the variables and between them and the loss rate; and

(c) using the principal components analysis technique (Section 5.7.2).

The categorisation was in two steps. The storm variables were categorised in the first step (Sections 6.4.4 and 6.4.5) and the catchment variables in the second (Section 6.4.6). This produced seven groups of variables. The regression analysis was then carried out on seven variables, each representing one of the different groups (Section 6.4.7).

6.4.2 Loss Rate Data

The loss rate data for the different analyses were the values calculated for the sixteen storms. Two physical phenomena prevented a complete data sample of loss rates from being obtained. One phenomenon was snowmelt, which twice caused "negative" loss rates in the Upper Motueka catchment; the snowmelt caused the surface runoff volume from the catchment to *exceed* the volume of storm rainfall input.

The second phenomenon was high abstraction effects in the two minor catchments. In the smaller storms, i.e. when the average Motueka rainfall depth was less than approximately 1 inch (25 mm), the volume of surface runoff outflow from a minor catchment was often *less* than the total volume of surface runoff inflow to the catchment from the upstream constituent catchment(s). This would occur despite the minor catchment having received at least ½ inch (13 mm) of rainfall. The phenomenon is attributed to leakage in the channels of the two minor catchments.

6.4.3 The Independent Variables

Seven storm and thirteen catchment variables were considered as possible independent variables for the regression analysis. Definitions of these variables are given in Table 6.5. The three temperature variables 9AMF, MAXF and MINF were only recorded at Golden Downs. This place is at an elevation of 900 ft (274 m) and is shown in Figure 4.17 as the site of the storage rainguage located some 3 miles (5 km) downstream of the Upper Motueka outlet. The readings for the temperature variables were assumed the same for each catchment in a storm.

6.4.4 Categorisation of the Storm Variables

The storm variables were categorised into groups after examining their inter-relationships and their influence on the loss rate in each of the constituent catchments and also in the Woodstock and Motueka catchments Considering each catchment individually, instead of collectively, removed any complications arising from the influence of different catchment characteristics on the loss rate.

The first part of the examination was the obtaining of the correlation matrix of storm variables for each catchment, using only those storms for which there was a positive loss rate. A typical result

TABLE 6.5

DEFINITIONS OF THE REGRESSION VARIABLES

Symbol			
LR	Catchment loss rate, in inches/hour - the dependent variable.		
	Storm Variables		
DEPTH	Weighted average rainfall depth, in inches.		
DURTN	Weighted average duration of storm rainfall, in hours.		
INT	Average storm rainfall intensity, in inches/hour.		
ATWET	Ratio of the rate of total runoff at the start of surface runoff to the true catchment area, in cusecs/square mile.		
9AMF	9 a.m. temperature reading nearest the middle of the storm, in ^{o}F.		
MAXF	Maximum temperature over the duration of the storm, in ^{o}F.		
MINF	Minimum temperature over the duration of the storm, in ^{o}F.		
	Catchment Variables		
EXOT	Percentage of a catchment in	exotic forest.	
NAT	" "	native forest.	
FERN	" "	fern.	
SCRUB	" "	scrub.	
GRASS	" "	grass.	
BARE	" "	bare ground.	
F1	" "	geological class	I
F2	" "	"	II
F3	" "	"	III
F4	" "	"	IV
F5	" "	"	V
F6	" "	"	VI
F7	" "	"	VII

is that shown for the Wangapeka catchment in Table 6.6. The table shows that for this particular catchment none of the storm variables was correlated with the loss rate at the 0.05 significance level. This was not always the case. However, the signs of the correlation coefficients in Table 6.6 between the variables and the loss rate are representative of the large majority of the results. In general, the loss rate was inversely related to the depth (DEPTH), duration (DURTN) and antecedent wetness (ATWET) variables, and positively related to the remaining variables

TABLE 6.6

WANGAPEKA CATCHMENT - Matrix of correlation coefficients, from considering eight variables and sixteen storms.

	LR	DEPTH	DURTN	INT	ATWET	9AMF	MAXF	MINF
LR	1.0							
DEPTH	-0.16	1.0						
DURTN	-0.46	0.65**	1.0					
INT	0.34	0.43	-0.37	1.0				
ATWET	-0.23	0.23	0	0.32	1.0			
9AMF	0.33	0.34	0	0.41	0.08	1.0		
MAXF	0.36	0.13	-0.32	0.50*	-0.14	0.79**	1.0	
MINF	0.08	0.48	0.16	0.38	0.27	0.79**	0.74**	1.0

Note: * and ** denote significant correlations at the 0.05 and 0.01 levels,respectively.

As illustrated in Table 6.6 the depth (DEPTH) and duration (DURTN) variables were significantly correlated, as were the three temperature variables 9AMF, MAXF and MINF. Although Table 6.6 shows the temperature variable MAXF and intensity INT as being significantly correlated, this is unrepresentative and it was regarded as a spurious correlation.

The second part of the examination involved the principal components analysis of the storm variables, using the storms which had positive loss rates. The analysis for each catchment yielded four principal components with maximum loadings of 0.50 or greater. The total variance explained by the four components was always greater than 95 percent. When the four components were rotated by the Varimax criteria a similar result was obtained for each catchment.

A typical result is that shown for the Wangapeka catchment in Table 6.7. The component loading matrix in Table 6.7 shows the same relationships between the storm variables as those exhibited in the correlation matrix in Table 6.6. This becomes evident in Section 6.4.5, which identifies and interprets the components in Table 6.7. Each component is identified according to its important variables. A loading of 0.80 was used to distinguish between important and unimportant variables in a component.

TABLE 6.7

WANGAPEKA CATCHMENT - The component loading matrix after Varimax rotation, from considering seven variables and sixteen storms.

	Temperature C_1	Storm Size C_2	Antecedent Wetness C_3	Intensity C_4
DEPTH	-0.22	$\underline{0.87}$	0.11	0.41
DURTN	-0.03	$\underline{0.93}$	0	-0.36
INT	0.29	-0.03	0.18	$\underline{0.93}$
ATWET	0.02	0.06	$\underline{0.98}$	0.15
9AMF	$\underline{0.92}$	0.11	0.03	0.14
MAXF	$\underline{0.89}$	-0.19	-0.21	0.30
MINF	$\underline{0.90}$	0.25	0.23	0.09

Note: a. The total variance explained by the four components = 96.4 percent.

b. Loadings considered important are underlined.

Also given in Section 6.4.5 is a brief physical explanation for the direction of the relationship between the loss rate and the storm variables as found in the correlation matrices.

6.4.5 Identification of the Components in Table 6.7

Component No.1 - Temperature

Important loadings for the three temperature variables (9AMF, MAXF and MINF) occur in the same component (C_1). This indicates that the three variables are closely related, which is not surprising in view of their similar nature. Confirmation of the close relationships between the variables was found in the correlation matrices (see Table 6.6). The occurrence of important loadings for the three variables in the first component identified the component with storm temperature.

Temperature influences infiltration by affecting evapotranspiration, the viscosity of water and the condition and structure of the soil. Thus the loss rate tends to be greater with higher temperatures and usually exhibits a cyclic variation with season (Laurenson and Pilgrim, 1962; Karoly, 1965). The trend of higher loss rates with higher temperatures was evident in the Motueka storm data. This is shown by the typical results in Table 6.6 where the loss rate is positively related to the temperature variables.

Component No.2 - Storm Size

The second component C_2 was called storm size, since the two important variables in this component are the average duration (DURTN) and depth (DEPTH) of the storm rainfall. Both variables are indicators of the size of the storm, with a greater storm duration often meaning a greater depth of rainfall. This type of relationship between the two variables existed in the Motueka storms, as illustrated by their high loadings with the same sign in the second component and by the significant, positive correlation between them in Table 6.6.

Increases in the two variables mean a replenishment of the soil moisture storage and, hence, a lowering of the infiltration capacity of the soil. The loss rate therefore tends to be less for greater storm durations and rainfall depths. This kind of behaviour would account for the loss rate in the Motueka catchment being inversely related to the DEPTH and DURTN variables (see Table 6.6).

Component No.3 - Antecedent Wetness

The third component C_3, having only ATWET as an important variable, was identified with the antecedent wetness of a catchment.

It is well established that if a catchment is wet prior to a storm the initial and, hence, the average infiltration capacity of the soil during the storm is lower. Consequently, the loss rate is lower for greater antecedent wetness values. Such a trend was apparent in the Motueka catchment, as shown by the inverse relationship between ATWET and the loss rate in Table 6.6.

Component No.4 - Intensity

The fourth component C_4 was called intensity, in view of INT being its only important variable.

As illustrated by the positive relationship between INT and the loss rate in Table 6.6, the loss rate in the Motueka catchment tended to increase with increasing storm intensity. This loss rate behaviour was attributed to the high proportion of cover, especially forest, and alluvial gravels in the catchment allowing the average infiltration rate (i.e. the loss rate) to increase with the average rate of rainfall on the catchment (i.e. the storm intensity). Similar loss rate behaviour has been reported by Karoly (1965) and Rao et al (1974).

From this identification of the components in Table 6.7, and in view of the reasonable physical explanation for each component and its characteristic influence on the loss rate, the seven storm variables were recognised as belonging to four groups. These groups are shown in Table 6.8.

TABLE 6.8

GROUPING OF THE STORM VARIABLES

Temperature	Storm Size	Antecedent Wetness	Intensity
9AMF	DEPTH	ATWET	INT
MAXF	DURTN		
MINF			

6.4.6 Categorisation of the Catchment Variables

The thirteen catchment variables were categorised into groups after the storm and catchment data from the five constituent catchments were examined collectively. Eight of the sixteen storms were used in the examination. These were the storms for which there was a positive loss rate for each constituent catchment.

As in Section 6.4.4 the first part of the examination was the obtaining of the correlation matrix (Table 6.9) of the data sample. Some of the correlations in Table 6.9 are spurious, e.g. where INT is correlated to F1 and F3 and where a land-use or land-type variable is correlated with another of its own type.

It is interesting to note in Table 6.9 that the storm intensity (INT) and antecedent wetness (ATWET) variables are significantly correlated with the loss rate, in the directions as already described in Section 6.4.5. Also of note is that, with the exception of NAT, the land-use variables which refer to land cover show a significant, positive correlation with the loss rate. This is consistent with the indication from Chapter 2 that increasing the cover in a catchment increases the loss rate. The negative coefficient for the correlation between NAT and the loss rate was unexpected and is difficult to explain physically.

A principal components analysis was then made of the seven storm and the thirteen catchment variables using the data for the eight storms. The analysis produced seven components with maximum loadings of 0.35 or greater. These seven components explained 97.6 percent of the total variance in the data of the corresponding correlation matrix. Varimax rotation of the seven components gave the component loading matrix in Table 6.10. A loading of 0.80 was again used to distinguish between important and unimportant variables in the different components. However, some consideration was also given to variables with lower loadings in identifying the components.

From Table 6.10 it can be seen that the four groups of storm variables decided on in Section 6.4.5, i.e. temperature, storm size,

TABLE 6.9

CORRELATION MATRIX, FROM CONSIDERING TWENTY ONE VARIABLES, EIGHT STORMS AND THE FIVE CONSTITUENT CATCHMENTS

	LR	DEPTH	DURTN	INT	ATWET	9AMF	MAXF	MINF	EXOT	NAT	FERN	SCRUB	GRASS	BARE	F1	F2	F3	F4	F5	F6	F7
LR	1.0																				
DEPTH		1.0																			
DURTN		0.71**	1.0																		
INT	0.50**	0.75**		1.0																	
ATWET	-0.55**				1.0																
9AMF		0.40*	0.53**			1.0															
MAXF		0.33*				0.65	1.0														
MINF		0.58**	0.68**			0.80*	0.68	1.0													
EXOT	0.32*								1.0												
NAT	-0.30				0.42*				-0.86	1.0											
FERN	0.33*								0.80	-0.64	1.0										
SCRUB	0.34*				-0.31*				0.55	-0.67	0.80	1.0									
GRASS	0.39*				-0.32*				0.95*	-0.82	0.87	0.72	1.0								
BARE									-0.34		-0.65		-0.44	1.0							
F1		0.30		0.33*	0.31*				-0.51	0.72			-0.32	-0.59	1.0						
F2									-0.36		-0.68	-0.32	-0.48	1.0**	-0.59	1.0					
F3				0.31*					0.35	-0.39	0.80	0.87	0.49	-0.43		-0.48	1.0				
F4					0.30				-0.59	0.86	-0.40	-0.48	-0.47	-0.39	0.80	-0.37	-0.35	1.0			
F5									-0.32		-0.67	-0.33	-0.45	0.99**	-0.63	1.0**	-0.49	-0.39	1.0		
F6					0.31*				-0.35	0.75		-0.54		-0.55	0.68	-0.52	-0.40	0.94*		1.0	
F7									0.87	-0.61	0.51		0.74	-0.33	-0.54	-0.31		-0.36			1.0

Note: a. For clarity correlation coefficients less than 0.30 are omitted.

TABLE 6.10

THE COMPONENT LOADING MATRIX AFTER VARIMAX ROTATION, FROM CONSIDERING TWENTY VARIABLES, EIGHT STORMS AND THE FIVE CONSTITUENT CATCHMENTS

	Land Use, Land Type C_1	Land Use, Land Type C_2	Temperature C_3	Land Use, Land Type C_4	Antecedent Wetness C_5	Storm Size C_6	Intensity C_7
DEPTH						-0.61	-0.70
DURTN						-0.95	
INT							-0.95
ATWET					0.93		
9AMF			0.82		0.34	-0.36	
MAXF			0.95				
MINF			0.77			-0.57	
EXOT	0.93			0.33			
NAT	-0.77	-0.32		-0.52			
FERN	0.56	-0.44		0.70			
SCRUB				0.91			
GRASS	0.81			0.46			
BARE		0.96					
F1	-0.66	-0.72					
F2		0.95					
F3				0.94			
F4	-0.54	-0.62		-0.52			
F5		0.96					
F6		-0.73		-0.62			
F7	0.96						

Note: a. The total variance explained by the seven components = 97.6 percent.

b. Loadings considered important are underlined.

c. For clarity loadings less than 0.30 are omitted.

antecedent wetness and intensity, are repeated by components C_3, C_6, C_5 and C_7, respectively. The remaining three components, i.e. C_1, C_2 and C_4, could only be broadly classified as land use-land type components. In view of these latter three components, three groups of catchment variables were recognised (see Table 6.11).

TABLE 6.11

GROUPING OF THE CATCHMENT VARIABLES

Land Use-Land Type Groups		
EXOT	BARE	FERN
NAT	F1	SCRUB
F7	F2	F3
	F4	
	F5	
	F6	

The grouping of the catchment variables in Table 6.11 was done according to the highest loading for each variable in Table 6.10. It will be observed from Table 6.9 that the variables within each group in Table 6.11 are closely related (often spuriously) with each other. This grouping of closely related variables was the purpose for which principal components analysis was employed and it demonstrates the usefulness of the technique.

6.4.7 The Loss Rate Equation

Four storm and three catchment variables were selected for the regression analysis to obtain the loss rate equation. The storm variables were MAXF, DURTN, ATWET and INT, each representing one of the groups in

Table 6.8. The catchment variables were EXOT, BARE and SCRUB. They were chosen as the most useful and meaningful representatives of the groups in Table 6.11.

The exotic forest variable EXOT was chosen ahead of the GRASS variable in the first group in Table 6.11, even though the latter variable was more highly correlated with the loss rate (see Table 6.9). The main reason for this was that the equation sought was intended to relate the loss rate with the percentage of a catchment in exotic forest, not grass. Moreover, the higher loading for EXOT in Table 6.10 suggested it was a more representative variable of the relevant group in Table 6.11. An implication of omitting GRASS from the regression analysis is discussed in Section 7.3.3.

A stepwise linear regression analysis (Draper and Smith, 1966) was carried out on the seven variables using the data for the eight storms and the five constituent catchments. The following loss rate equation was obtained from the analysis.

$$LR=0.0493-0.00644ATWET^{**}+0.796INT^{**}+0.00133EXOT^{*}-0.000803DURTN \qquad \ldots\ldots\ldots\ldots\ 6.4$$

where * and ** denote significant regression coefficients at the 0.05 and 0.01 levels respectively, and where

the multiple correlation coefficient = 0.73

the multiple correlation coefficient,
adjusted for the degrees of freedom (Weber et al, 1973) = 0.70

the adjusted standard error of estimate = 0.04 in/hr.

Equation 6.4 was selected at the step in the regression when the adjusted multiple correlation coefficient was a maximum. This selection criterion caused only four of the seven variables to appear in the final equation (Eq. 6.4).

The squares of the unadjusted and adjusted multiple correlation coefficients for Equation 6.4 are 0.53 and 0.49, respectively, indicating that Equation 6.4 explains approximately half of the total variance in the loss rate data. Further, the equation has a F-value of 9.69, which indicates that the equation is significant at the 0.001 level.

To gain an impression of the relative importance of each variable in Equation 6.4, an example calculation of a loss rate is given in Table 6.12. In this example the contributions to the loss rate from the ATWET, INT and EXOT terms are of the same order. The contribution from the DURTN term is of lesser importance.

TABLE 6.12

EXAMPLE CALCULATION OF THE LOSS RATE USING EQUATION 6.4

Example: Minor Woodstock catchment, storm no. 6.

				+0.0493
-0.00644ATWET	=	-0.00644x4.314	=	-0.0278
+0.796INT	=	+0.796x0.043	=	+0.0342
+0.00133EXOT	=	+0.00133x24.18	=	+0.0322
-0.000803DURTN	=	-0.000803x16.18	=	-0.0013
				0.0749

i.e. The loss rate calculated from Eq. 6.4 = 0.075

(The corresponding actual loss rate = 0.079)

Finally, the range which was present in the regression data sample for the different variables is given in Table 6.13. It is recommended that in any future use of Equation 6.4 the values for the variables should lie within the corresponding range in Table 6.13.

TABLE 6.13

RANGE IN THE REGRESSION DATA SAMPLE

Variable	Range	
	Imperial	Metric
LR	0.002-0.261 in/hr	0.05-6.63 mm/hr
ATWET	0.52-12.31 cusecs/sq.mile	0.0057-0.135 $m^3s^{-1}km^{-2}$
INT	0.04-0.16 in/hr	1.02-4.06 mm/hr
EXOT	0-24.18%	0-24.18%
DURTN	15.0-41.5 hrs	15.0-41.5 hrs

6.4.8 Illustration of the Use of Equation 6.4

The use of a loss rate-land use relationship like Equation 6.4 is illustrated with the sensitivity analysis that was made of the Baton catchment for storms no.6 and 13. The analysis produced the curves in Figures 6.13 and 6.16. For the two storms these curves qualitatively depict the hydrological response of the Baton catchment to afforestation in the upper and lower treatment regions. Equation 6.4 enables the responses to be quantified by providing a prediction of the increase in the loss rate following afforestation (see Figure 6.17).

As shown in Figure 6.17a, the loss rates estimated by Equation 6.4 for the Baton catchment for storms no.6 and 13 are 0.048 and 0.065 in/hr,

a. PREDICTED INCREASE IN THE LOSS RATE USING EQUATION 6.4

	Storm No.6	Storm No.13
Actual loss rate, in/hr	0.056	0.070
Loss rate estimated by Eq. 6.4 (EXOT=0), in/hr	0.048	0.065
Loss rate predicted by Eq. 6.4 for 25% exotic forest (EXOT=25), in/hr	0.081	0.098
∴ Predicted increase in the loss rate for 25% exotic forest, in/hr	0.033	0.033
Predicted increase in the loss rate in relation to the actual loss rate	58.9%	47.1%

b. QUANTIFIED HYDROLOGICAL RESPONSES USING FIGURES 6.13 AND 6.16

Response	Storm No.6		Storm No.13	
	Upper Region	Lower Region	Upper Region	Lower Region
Reduction in surface runoff peak	13.3%	8.9%	10.2%	15.1%
Reduction in suspended sediment quantity	12.2%	9.4%	19.2%	23.3%

FIG. 6.17 : PREDICTION OF THE HYDROLOGICAL RESPONSES TO AFFORESTATION IN THE BATON CATCHMENT FOR STORMS NO.6 AND 13.

respectively. It can be seen that these values compare favourably with the corresponding actual loss rates. The values refer to present conditions, i.e. with no exotic forest in the catchment (EXOT=0). For future afforestation in either of the catchment's land treatment regions, each of which cover 25 percent of the catchment, the loss rates predicted by Equation 6.4 (using EXOT=25) for storms no.6 and 13 are 0.081 and 0.098 in/hr, respectively. Thus Equation 6.4 predicts that, for each storm, the increase in the loss rate following afforestation would be 0.033 in/hr. In relation to the actual loss rates for storms no.6 and 13, this is an increase of 58.9 and 47.1 percent, respectively, in the storm loss rates.

When these percentage increases in the loss rate are applied to the relevant sensitivity analysis curves (Figures 6.13 and 6.16), the reductions in surface runoff peak and the quantity of suspended sediment following afforestation can be quantified. Figure 6.17b summarises these reductions. It shows, for example, that for storm no.6 there would be a slight benefit in flood protection if the upper treatment region rather than the lower region of the Baton catchment was afforested.

The variability of the results in Figure 6.17b between the two storms emphasises that, when an afforestation programme is considered for a catchment, a sensitivity analysis should be made of a number of representative storms.

CHAPTER 7

EVALUATION OF RESULTS

The Motueka model satisfied the needs of this investigation.

Firstly, it performed well in reproducing the surface runoff hydrographs of the four test storms. The quality of the reproductions is evaluated in Section 7.1.1, while other aspects of the reproductions are discussed in the remainder of Section 7.1.

Secondly, the model enabled a sensitivity analysis to be performed of any part of the catchment and also allowed different forms of land treatment to be considered. Section 7.2 covers features and implications of the sensitivity analysis results.

A basic premise in performing the sensitivity analyses was that the loss rate is a suitable parameter for expressing the effects of land-use changes. The premise is supported by the loss rate results, which are evaluated in Section 7.3.

7.1 THE MOTUEKA MODEL

7.1.1 Evaluation of Performance

The performance of the Motueka model in reproducing surface runoff hydrographs was evaluated by the system shown in Figure 7.1. For each of the twenty hydrographs reproduced in the testing of the model (Section 6.2) the corresponding model efficiency and the absolute variation in surface runoff peak were plotted against each other. The location of the plotted point classified the quality of the reproduction and the model's performance.

SUMMARY	
Evaluation	No. of reproductions
Excellent	4
Good	7
Satisfactory	3
Poor	6
Very poor	0
	20

LEGEND

Storm no. 6 — ×
" " 13 — •
" " 21 — +
" " 24 — ⊡

Reproduction at Upper Motueka outlet — UM
" " Wangapeka outlet — WA
" " Baton outlet — BA
" " Woodstock — WD
" " Bluegum Corner — BC

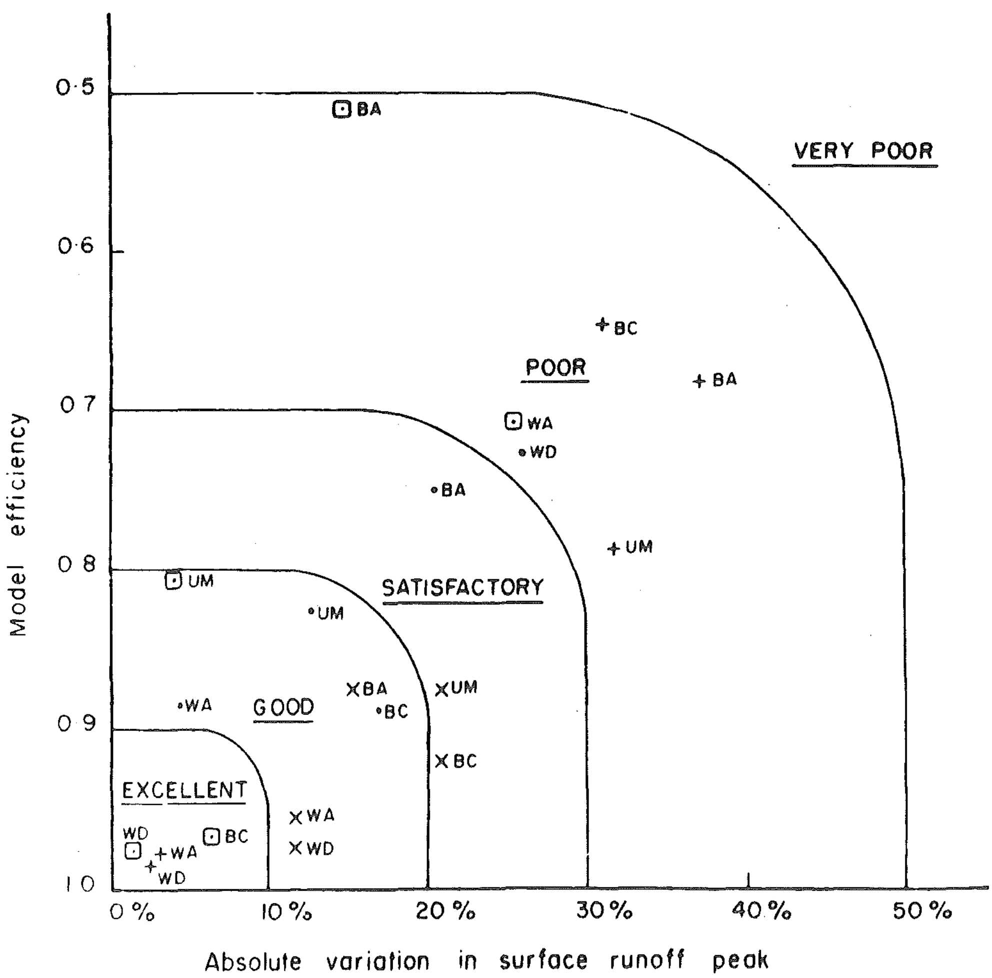


FIG. 7.1 : EVALUATION OF THE MOTUEKA MODEL

The five evaluation classes used are indicated in Figure 7.1. The limits of each class were set arbitrarily after finding that they agreed well with a visual impression of the reproductions.

The evaluations of the reproductions by the model are summarised in Figure 7.1. The model reproduced surface runoff hydrographs of variable quality, ranging from excellent to poor, but its overall performance was considered satisfactory. It will be noted that, for each of the sensitivity analyses performed in this study (Section 6.3), the model gave at least a satisfactory performance (according to Figure 7.1) in reproducing the relevant surface runoff hydrograph.

There was no marked difference in quality between the reproductions from the modified isochronal approach and the reproductions dominated by the sub-catchment approach, i.e. those at Woodstock and Bluegum Corner. Both approaches produced hydrographs that fell into the top four evaluation classes.

An especially encouraging feature was the excellent reproductions at the outlets of the two largest catchments, i.e. at Woodstock and Bluegum corner, for the largest storm (no.24). This suggests that the previously neglected sub-catchment approach is applicable to large catchments and that it performs better in the larger storms. The findings expressed in Section 7.1.3 reinforce this latter point.

With all models there are two major sources of error, the input data and the model itself. Imperfections in the hydrograph reproductions by the Motueka model can be attributed in many instances to errors in the first source (see Section 7.1.2). Imperfections arising from the second source were also evident (Sections 7.1.3 and 7.1.4).

7.1.2 Input Data

The main input data to the Motueka model were the rainfall excess hyetographs. Their determination was constrained in three ways and this affected the quality of the hydrograph reproductions.

The first constraint was posed by the pluviometers. Although there were more of them than for any other New Zealand catchment of similar size, they were poorly distributed. Most of the pluviometers were grouped near the catchment outlet away from the higher rainfall areas, and only two pluviometers were located within the catchment itself (see Figure 4.17). Further, at times some of the pluviometers did not function; for the test storms the average number of pluviometers which functioned in a storm was six. Thus, the average pluviometer coverage for the catchment of one per 87 square miles (225 km^2) is a little misleading. A more strategic placing of the catchment's nine pluviometers would have improved the hydrograph reproductions.

The poor pluviometer distribution would have affected most of all the models of the relatively small Upper Motueka, Wangapeka and Baton catchments, whose streamflow responses to rainfall were reasonably sensitive. Reproducing these responses required accurate information on rainfall intensities. However, because of malfunctions in the single pluviometer in each of the Upper Motueka and Baton catchments, sometimes it was even necessary to take this information from records of pluviometers located outside the Motueka catchment altogether. For example, for storms no.6 and 21 it was necessary to obtain the rainfall intensities for the Baton and Wangapeka models from the records for the Cobb Dam pluviometer (see Figure 4.17). This pluviometer is located

8 miles (13 km) from the Baton catchment and 20 miles (32 km) from the Wangapeka catchment.

These approximations in determining the rainfall intensities for the three catchment models were very large in comparison with those made in the testing (Laurenson, 1962) of the original Laurenson model on the 35 square mile (90 km^2) South Creek catchment. For this catchment rainfall intensity data were available for up to as many as five pluviometers.

The second constraint on the rainfall input data in this study was the lack of information on storm depths in the Upper Motueka, Wangapeka and Baton catchments. There was only one source (pluviometer or storage rainguage) of such information in each of these three catchments, and each source was located near the catchment outlet. Consequently, the construction of the storm isohyetal map over the headwaters of each catchment, normally the region of highest rainfall, was always very subjective. This would have been detrimental to the performances of the models of the three catchments.

The third constraint was the decision to use one loss rate per storm to generate the rainfall excess in a constituent model. The use of a constant loss rate inherently causes an over-estimation of the rainfall excess at the start of a storm and an under-estimation of it near the end (see Figure 3.3). The effect of this is exhibited by the Baton hydrograph for storm no.13 (see Figure 6.4). The first routed peak is an over-estimate and, conversely, the second is an under-estimate. However, it was found that when a separate loss rate could be applied for each rise of a hydrograph the reproduction improved (Section 6.2.3).

Errors in the hydrograph reproductions resulting from erroneous input were not confined to the smaller catchments. An example of this is the uncharacteristically poor reproduction at Woodstock for storm no.13 (Figure 6.5). For the other three test storms the reproductions at this gauging station were either excellent or good on the evaluation scale (Figure 7.1), indicating that the fault in this case was non-representative rainfall excess input data.

7.1.3 Effects of Errors in the Reservoir Locations

With the rainfall excess for each sub-area in the Laurenson model assumed concentrated at the reservoir location, it is implicitly assumed that the reservoir location represents the spatial average relative travel time for the sub-area. If the reservoir location is an under-estimate of this time, the routing of the sub-area rainfall excess through the reservoir will insufficiently account for the travel time of the rainfall excess from that sub-area into the next one downstream. Thus, the net result of a reservoir location being under or over-estimate could be an early or late routed hydrograph, respectively.

For example, the faulty early rise preceding the proper rise in the routed hydrographs at Bluegum Corner for storms no.6 and 21 (Figures 6.3 and 6.7) is attributed to some reservoir locations in the Minor Motueka model being under-estimates of the sub-area average relative travel times. Optimisation of the reservoir delay time-discharge equation (Eq. 3.11) did not eliminate the faulty early rise. For in doing so, it would have adversely affected the large routed hydrograph contribution from the Woodstock catchment which had been properly lagged.

Since travel time decreases with increasing discharge (Eq. 3.9) the fault would appear to be a minor one. The actual error in the travel time of the routed rainfall excess, arising from an error in the estimation of the sub-area's average relative travel time, would be less for a larger discharge. Hence, the detrimental effect on the routed hydrograph of reservoir location errors should diminish with increasing storm size. This point is borne out by the routed hydrographs at Bluegum Corner for the test storms. The early rise phenomenon is very pronounced (see Figure 6.7) for storm no.21, the smallest storm, it is less pronounced (see Figure 6.3) for storm no.6, and for the two largest storms (nos. 13 and 24) it is virtually undetectable (see Figures 6.5 and 6.9).

Reservoir location errors are more likely to occur in the sub-catchment approach. Unlike the modified isochronal approach, the sub-areas are usually few and large and can show a wide variation in relative travel time. It should be possible to remedy the effects of reservoir location errors by simply increasing the number of sub-areas. This would lessen the variation in relative travel time in a sub-area and improve the estimation of the average time for the sub-area. Since the greatest differences in relative travel time occur in the flat areas near the catchment outlet (see the isochronal sub-area patterns in Figures 4.19-4.21), increasing the number of sub-areas in this part of the catchment should have the most beneficial effect on the routed hydrograph.

7.1.4 The Routed Recessions

The tails of the routed hydrographs receded at a slower rate than the actual hydrographs (see Figures 6.3 and 6.4). This effect was not serious, since the emphasis with the model was on the reproduction of the timing and peak of the hydrograph. The effect is a characteristic of the routing equations (Eqs. 3.12-3.16) and has been explained by Laurenson (1962). It arises partly from the fact that as the discharge approaches zero, the reservoir delay time approaches infinity (see Eqs. 3.15 and 3.16) and thus c approaches unity (see Eq. 3.14). Further, in the region of the hydrograph tail Equation 3.12 reduces to

$$q_2 = cq_1 \qquad \qquad \text{..........} \quad 7.1$$

If c was constant Equation 7.1 would produce a typical depletion curve (e.g. Eq. 5.1). However, the routed hydrograph tail approaches zero more slowly than does such a curve because c is not constant, but increasing.

After using the Motueka model to reproduce the surface runoff hydrographs for storm no.6 and those for the Upper Motueka, Wangapeka and Baton catchments for storm no.13, the runoff routing procedure was amended slightly to reduce the length of the recessions of the remaining routed hydrographs. The amendment significantly decreased the routing computation time (by about 25 percent) and improved the efficiency of the optimisation procedure. It involved an approximation of the routed recession in each sub-area to the effect that, past the end time of the actual surface runoff, the recession conformed to a depletion curve (Eq. 5.1) whose hourly depletion ratio (k_r) was an assumed 0.90. Because this ratio did not always coincide with that of the preceding part of the recession, a minor kink occasionally appeared in the routed hydrograph tail at the end time of the actual surface runoff (e.g. Figure 6.5).

7.1.5 Optimisation

There are two obvious advantages in employing the optimisation procedure. Firstly, it means that the operation of a Laurenson model for the reproduction of a surface runoff hydrograph no longer requires an empirical lag-mean discharge relationship. Having to obtain such a relationship when reproducing hydrographs has been a practical drawback to the use of the model.

The second advantage is that, by deriving the optimum reservoir delay time-discharge equation (Eq. 3.11) for the particular storm, the procedure allows the model always to perform at its maximum level.

The benefits of optimisation can be seen by comparing Figures 6.1 and 6.2. The figures show initial and optimum routed hydrographs for storm no.6. It is clearly evident that the optimum hydrographs (Figure 6.2) are of a superior quality.

It may be noted from the table accompanying the two figures (Table 6.3) that the quality of the hydrograph reproduction was reasonably sensitive to the A and B values. In the case of the Wangapeka catchment, for example, optimisation increased the initial A and B values by 55 and 41 percent, respectively, and this produced almost a trebling in the efficiency index for the goodness-of-fit of the hydrograph reproduction.

The optimum A and B values that were obtained for the four test storms are summarised in Table 7.1. An inspection of the wide variation in the A and B values reveals two trends. Firstly, the increase in A for a constituent model is generally accompanied by an increase in B, suggesting that the two parameters are interdependent. Recent work in

TABLE 7.1

THE OPTIMUM A AND B VALUES FROM TESTING THE MOTUEKA MODEL

Optimum A and B Values	Constituent Model				
	Upper Motueka	Wangapeka	Baton	Minor Woodstock	Minor Motueka
Storm No.6					
A	126.5	145.6	33.7	43.4	4419
B	0.438	0.345	0.235	0.254	0.649
	(0.51)	(1.58)	(0.68)	(0.49)	(0.55)
Storm No.13					
A	411.2	196.8	394.7	103.4	210.5
B	0.563	0.344	0.572	0.218	0.245
	(0.95)	(1.83)	(1.37)	(1.64)	(1.67)
Storm No.21					
A	18.5	38.8	54.4	7.65	135.4
B	0.046	0.143	0.281	0.013	0.298
	(0.16)	(0.53)	(0.94)	(0.30)	(0.35)
Storm No.24					
A	65.7	214.8	60.0	97.5	202.0
B	0.285	0.337	0.281	0.242	0.280
	(3.51)	(2.37)	(0.95)	(1.69)	(1.79)

Note: The average rainfall excess depth in inches for the corresponding true catchment is given in brackets. It is an index of the size of the storm in the true catchment.

Australia by Boyd (1973) and Aitken (1970, 1975) has substantiated this point.

Secondly, the increase in A and B for a model tends to follow an increase in the storm rainfall excess depth in the true catchment, which suggests that the two parameters increase with storm size. This supports the contention made in introducing the optimisation idea (Section 4.2.2.2) that the travel time-discharge relationship (Eq.3.9), on which the reservoir delay time equation (Eq. 3.11) is based, varies for different storms. A striking exception to this trend of A and B increasing with storm size is the case of the Minor Motueka model for storm no.6. However,in this instance the relevant A and B values in Table 7.1 are probably not the true optimum ones, since the optimisation was terminated by the second criterion (Section 5.4).

The interdependency between A and B is an important point. It was evident in the early model trials where it was observed that A and B have a similar but opposite effect on the routed hydrograph. For example, the routed peak can be increased and the time of rise reduced by a decrease in A or an increase in B. Therefore the optimisation procedure may have sought the optimum ratio between the two parameters, rather than their absolute optimum values (Ibbitt, 1972). If this was so, it is the ratio of the optimum A and B values that is of most interest, and it is this ratio which should be considered in any attempt to relate the parameters with storm characteristics.

To see whether there might be a relationship between the parame and storm size, the ratios of the A and B values in Table 7.1 were plotted against the corresponding storm rainfall excess depths. The results of this are shown in Figure 7.2. The two fitted lines in Figure 7.2 indicate that significant correlations between the ratios and the rainfall excess depths were found for the Wangapeka and Baton catchments. For the Wangapeka catchment the correlation is significant at the 0.05 level, while for the Baton catchment it is significant at the 0.10 level. The fitted lines suggest that the optimum A/optimum B ratio increases with increasing storm size. The difference in slope between the two lines is thought to be due to the differences in the topographical characteristics of the two catchments.

Four points per catchment is not a large enough sample with which to verify the existence of a relationship between the A and B parameters and storm size. Nevertheless, the two significant correlations in Figure 7.2 between the optimum parameter ratio and the rainfall excess depth encourages further research into this subject.

7.1.6 Equation 3.5

Equation 3.5 was a useful starting point for determining the optimum A and B values. However, the use of the equation itself, without optimisation, in a Laurenson model of a New Zealand catchment (Section 6.2.1) needs to be qualified in view of the very poor surface runoff hydrograph reproductions in Figure 6.1.

In using Equation 3.5 to obtain the reproductions in Figure 6.1 two assumptions were made. Firstly, it was assumed that the equation, although it refers to direct runoff, was also applicable to surface runoff. As mentioned in Section 6.1, this assumption appeared reasonable. Secondly, it was assumed that the equation could be applied to catchments

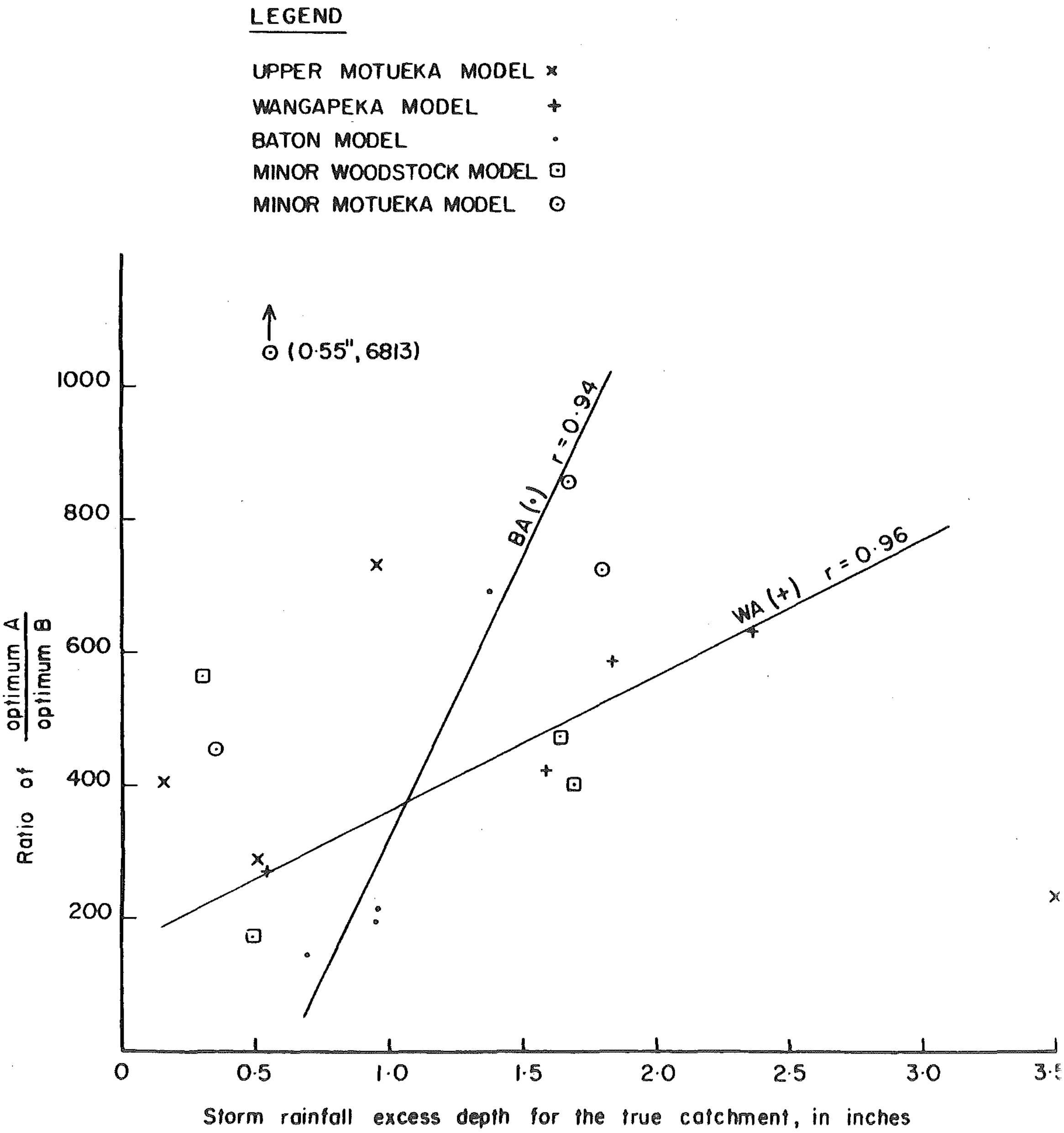


FIG. 7.2 : CORRELATION OF $\frac{\text{OPTIMUM A}}{\text{OPTIMUM B}}$ RATIO WITH STORM SIZE

of the size and with the slopes of the Upper Motueka, Wangapeka and Baton. But the areas for these three catchments are greater than the upper limit of 50 square miles (130 km^2) recommended for substitution into Equation 3.5, although the Upper Motueka and Baton catchment areas are close to this limit. Moreover, the values for the three catchments for the overland slope factor S_s (defined in Eq. 3.6) are an average 2.5 times greater than the upper limit of 0.14 recommended for use in Equation 3.5.

Because of this rather tenuous second assumption, the very poor reproductions in Figure 6.1 indicate only that Equation 3.5 should not be applied to catchments with areas and overland slopes greater than those recommended. They do not rule out the possibility of the equation being suitable for predicting A and B for small (<50 sq. miles or 130 km^2), flat (S_s <0.14) New Zealand catchments.

There appear to be problems in using a similar approach to predict A and B for the larger New Zealand catchments. First of all, there is likely to be some difficulty in establishing a general lag-topographical relationship, similar to Equation 3.5, for the larger catchments. This is indicated by the weak correlations found between the lag and the mean discharge in the Motueka catchments (see Table 7.1). However, it may be possible to establish lag-topographical relationships on a seasonal basis. This point is supported by the improvement that was obtained in the lag-mean discharge correlations for the Woodstock and Motueka catchments when only the summer storms were considered (see Table 6.2).

A second problem is that in using a lag-topographical relationship in the form of Equation 3.5 it is necessary to assume that A and B remain constant for different storms. Results of this study (Table 7.1) indicate though that the two parameters vary from storm to storm, with a tendency to increase with increasing storm size. A solution here could be to incorporate a storm size parameter as another independent variable in the lag-topographical relationship.

However, it seems from Section 7.1.5 that the most satisfactory solution to predicting A and B for ungauged catchments lies in relating optimum A and B values, or their ratio, with both storm and catchment characteristics. The fact that the resulting relationship would be based on optimum parameter values would remove the need to assume,as is the case with a time-average relationship like Equation 3.5, that the predicted A and B values are applicable in an instantaneous situation in the Laurenson model (Section 3.4.3).

7.2 THE SENSITIVITY ANALYSIS RESULTS

7.2.1 General

The purpose of the sensitivity analyses (Section 6.3) was to demonstrate the technique. Features of the technique that were demonstrate include:

(a) the flexibility of the technique - different forms of land treatment can be simulated and there is no restriction on the number or arrangement of the sub-areas involved in a simulation;

(b) the type of results obtainable; and

(c) the interpretation of results.

Basic assumptions with the technique are that the change in loss rate accounts for all the effects of the change in land use, and that the travel time-discharge relationship (Eq. 3.9) which exists for the storm concerned is unaltered by the land-use change. The validity of the latter assumption is unproven, but the assumption appears reasonable when a rural catchment is subjected to the vegetal and mechanical land treatments simulated in this study. However, it would be unwise to make the same assumption when a drastic land-use change like urbanisation is involved. Indeed Aitken (1975) recently found that the average value of A for a catchment increases with the proportion of a catchment urbanised

7.2.2 Suspended Sediment Quantities

It is emphasised that all the suspended sediment quantities were determined with the Woodstock rating curve (Eq. 4.1). The curve was used in the absence of similar curves for the other gauging stations. Thus, while it has been shown how a rating curve can be used to gain information on the suspended sediment response to land treatment, no quantitative significance can be attached to the suspended sediment results in this study. All remarks concerning the relative sensitivity of the different treatment regions are based only on the surface runoff peak results.

A second point is that the reductions in the suspended sediment quantities in the land treatment simulations were determined from the reductions in surface runoff. Hence, for afforestation, the quantities do not wholly account for the obvious physical effects that forests have in retaining erodible material. Consequently, if the correct rating curves were applied the estimates of the suspended sediment reductions would be conservative.

One further aspect is that it is not always justified to apply the one suspended sediment rating curve throughout the length of the flood hydrograph. This is because water often finds much more material ready to move at the beginning of the storm than at the end. Hence, the application of a rating curve requires consideration of such factors as the accuracy of the curve and at what times in the floods the suspended sediment sampling was done.

7.2.3 Shape of the Sensitivity Analysis Curves

Because of the typically peaked shape of rainfall excess hyetographs each uniform increase in loss rate produces less rainfall excess (surface runoff). This is reflected in the sensitivity analysis curves (Figures 6.11-6.16), which characteristically exhibit a decreasing rate in the surface runoff peak reductions with increase in loss rate. In the extreme case when no further reduction occurs with increase in loss rate, the loss rate has actually reached a value that eliminates all rainfall excess in the treatment region.

7.2.4 Influence of Catchment Storage

A finding of the sensitivity analyses was that under normal storm rainfall conditions the upper treatment regions of the catchments examined were more hydrologically sensitive to the land treatments than the corresponding downstream regions. This is shown by the results for: the analyses involving storm no.6 and vegetal land treatment (see Figures 6.11-6.13), and the analysis involving storm no.24 and mechanical land treatment (see Table 6.4).

This situation of the upper treatment regions being more hydrologically sensitive is attributed to the greater rainfall and slopes in the upper regions and to a relatively small catchment storage effect. The minor influence of catchment storage on the results was surprising. It was thought that, with catchments the size of those in the Motueka (especially the Motueka itself), the catchment storage influence in suppressing the effects of land treatments in the upper regions would be more dominant.

The obvious inference from the sensitivity analysis results is that the Motueka catchment and those within it are hydrologically small.

7.2.5 Mechanical Land Treatment

The results of the mechanical land treatment (Table 6.4) contrast sharply with those from Leopold and Maddock's (1954) study. For a hypothetical catchment of similar size (600 sq. miles or 1554 km^2), they found that the effect of dams in reducing peak flows was only local and diminished rapidly downstream. The probable explanation for the disagreement in results between this study and theirs is the smaller catchment storage influence in the Motueka and the fact that they used spatially uniform rainfall excess.

7.3 THE LOSS RATE RESULTS

7.3.1 Single vs. Multiple Loss Rates

Although it was possible on occasions to derive multiple loss rates (Section 6.2.3) for an upstream catchment (Upper Motueka, Wangapeka or Baton), such loss rates were not used in the loss rate analysis (Section 6.4). Each loss rate used referred to the whole storm and not to an individual rainfall burst. This was necessary in order to maintain a uniform set of loss rate data, since it was not possible to derive multiple loss rates for the Minor Woodstock and Minor Motueka catchments. Using a uniform loss rate data set avoided the introduction of unnecessary bias into the loss rate analysis.

The use of multiple loss rates for a storm in place of a single loss rate gives a more representative picture of the infiltration behaviour throughout the storm. It therefore improves hydrograph reproductions (Section 6.2.3). However, because the single loss rate in effect is the result of an averaging of the multiple loss rates it is considered that, as far as the loss rate analysis is concerned, the use of single loss rates detracted little, if anything, from the results.

7.3.2 Encouraging Features

The loss rate results are encouraging from many aspects. Firstly, the loss rate appears to be a satisfactory land-use index, contrary to earlier suggestions (e.g. Boughton, 1970). The loss rate was found to be significantly and positively correlated with the percentages of a catchment in exotic forest, grass, fern and scrub (see Table 6.9). Because there are spurious relationships between these variables, e.g. exotic forest and grass, it is possible however that the loss rate may not actually be dependent on all these variables.

A second indication of the potential of the loss rate as a land-use index was given via the loss rate equation (Eq. 6.4). In using the equation to quantify some of the sensitivity analysis results the loss rate was shown to be noticeably affected by afforestation (Figure 6.17).

The loss rate equation itself is highly significant. Further, the equation's independent variables, and the directions in which they are related to the loss rate, are strongly justifiable in physical terms (Section 6.4.5 and 6.4.6). There is also statistical support for the independent variables; the regression coefficients for the

ATWET, INT and EXOT variables are significant at least at the 0.05 level, while the coefficient for the DURTN variable is significant at the 0.10 level.

Support for the predictive use of the equation is given by its F-value (9.69). This value is almost 4 times (3.7) greater than that for an acceptable significance level (taken here as 0.05). According to one criterion (Draper and Smith, 1966, p.64), this suggests that the equation is a satisfactory predictor.

To evaluate the accuracy of Equation 6.4, loss rates estimated from the equation were plotted against the corresponding observed values from which the equation was obtained. Figure 7.3 shows the resulting scatter diagram. The plotted points in Figure 7.3 are randomly scattered about the 45° line, indicating that the form of Equation 6.4 is basically correct and that its predictions would contain little bias. An examination of the randomness of the residuals, i.e. the differences between the estimated and corresponding observed loss rates, gave the same indication (see Figure 7.4).

7.3.3 Uncertainties With Equation 6.4

There are areas of uncertainty with Equation 6.4. Firstly, it lacks precision, as shown by the range of scatter of the points about the 45° line in Figure 7.3 and about the zero horizontal line in Figure 7.4. The equation explains approximately only half of the total variance in the observed loss rate data, and the standard error of estimate is 50 percent of the mean loss rate value.

The principal uncertainty stems from the correlations between the EXOT and the F7 and GRASS variables. The EXOT variable was significantly

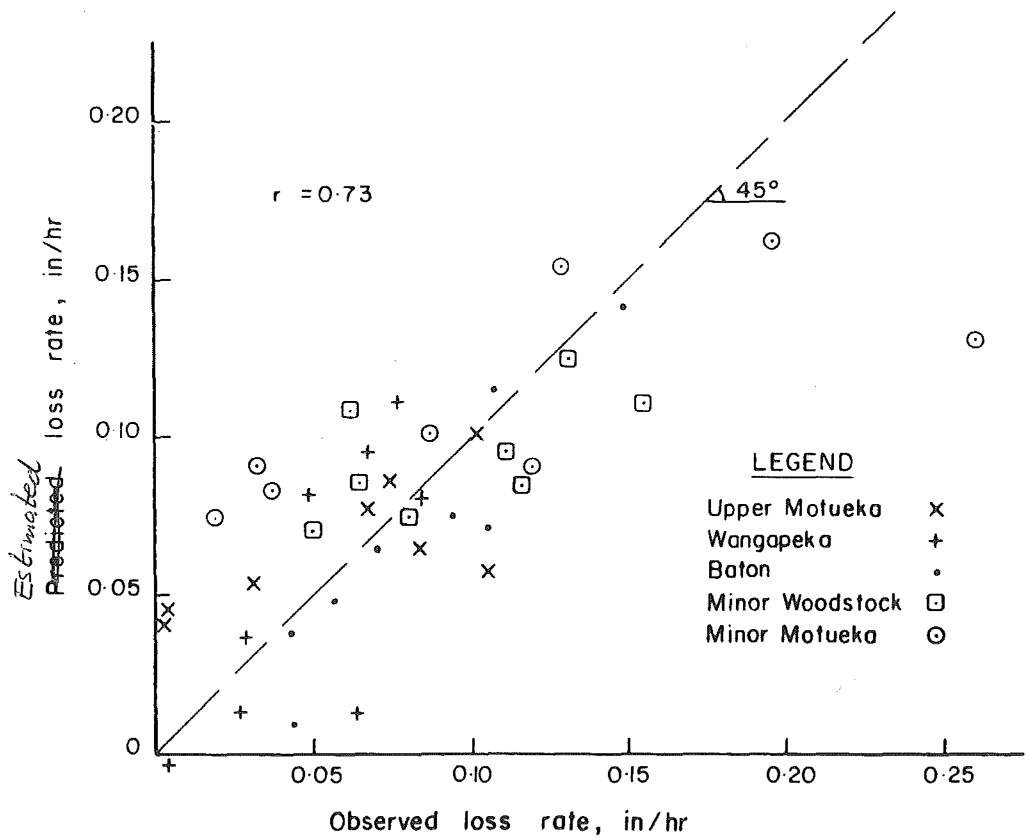


FIG. 7.3 : SCATTER DIAGRAM FOR EQUATION 6.4

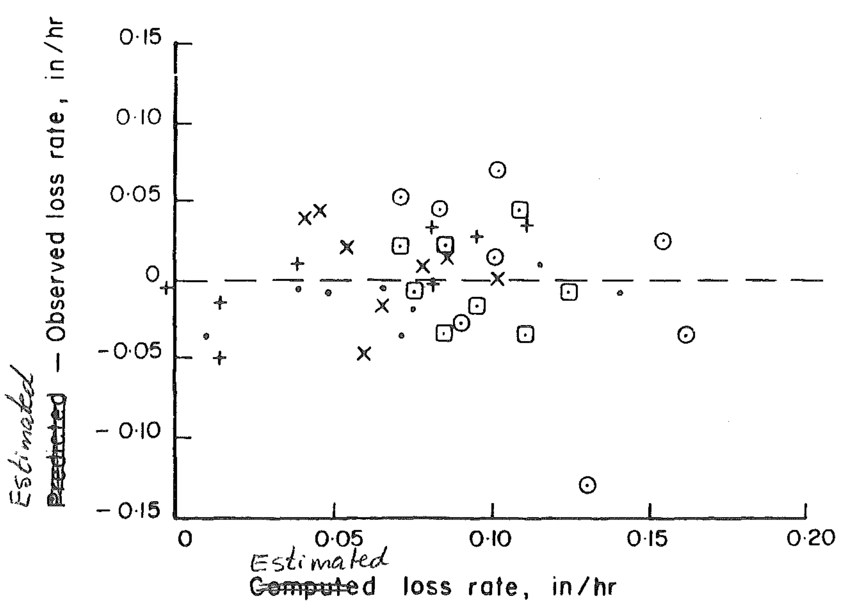


FIG. 7.4 : EXAMINATION OF THE RESIDUALS FROM EQUATION 6.4

correlated with the F7 variable at the 0.10 level and spuriously with the GRASS variable at the 0.05 level (see Table 6.9). Of the three variables only EXOT was entered into the regression analysis (Section 6.4.7). This was done in order to minimise multicollinearity (Section 5.7.2), with EXOT being chosen because it was the variable in which there was most interest. However, F7 represents the percentage of a catchment in alluvial gravels, while GRASS represents the percentage of grassed, cultivated and agricultural land. Increases in both the variables can also be expected to increase the loss rate. Therefore, because of the correlation between these variables and EXOT, the EXOT term in the loss rate equation may not truly reflect the influence of exotic forest alone on the loss rate - it may also reflect indirectly the influence of the other two variables.

7.3.4 Further Investigation

The uncertainties mentioned in Section 7.3.3 lessen the acceptability of Equation 6.4 as a predictor of the change in the loss rate following a change in exotic forest cover. The equation was valuable in this study for demonstrating the proposed method of making quantitative predictions on the effects of land treatment (Section 6.4.8). The actual results of the demonstrations though must be regarded with caution. Clearly, further investigation into loss rate behaviour is needed to obtain a reliable loss rate-land use relationship. However, the many favourable aspects with the loss rate results (see Section 7.3.2) suggest that such investigation would be worthwhile.

To overcome the problems encountered in this study caused by many of the catchment variables being closely and sometimes spuriously related, a greater number of catchments should be used in any future loss rate analysis. This and a greater number of storms would also enhance the likelihood of a precise loss rate equation being obtained.

Another factor that should improve a future loss rate equation is the use of a separate storm temperature value for each catchment considered in the loss rate analysis. In this study the temperature variable entered into the regression analysis (MAXF) did not appear in the regression equation (Eq. 6.4), in spite of temperature proving to be an important storm variable in each of the individual catchments (Section 6.4.4 and 6.4.5). The non-appearance of MAXF was presumably the result of the need to assume that the MAXF values recorded at Golden Downs were the same for each catchment (Section 6.4.3). While this assumption was satisfactory for examining the loss rate behaviour in each individual catchment, it may have been seriously in error when the loss rates for all the constituent catchments were analysed collectively in the regression analysis (Section 6.4.8). Indeed, the variations in temperature with the elevations of the constituent catchments probably obscured any correlation in the analysis between the temperature variable (MAXF) and the loss rate.

A generally applicable loss rate equation, which should be the aim of future analyses, is desirable for a number of reasons. It would mean that quantitative predictions could be made from sensitivity analyses involving different forms of vegetal land treatment. Moreover, it would lead to more realistic catchment modelling, by enabling spatial variations in losses to be taken account of. This could be achieved by using the equation to obtain loss rates for the individual sub-areas of a catchment, with a sub-area's loss rate depending on the cover, topography and the

the storm characteristics in the sub-area. Further, such an equation would be a useful aid in general hydrological design.

CHAPTER 8

SUMMARY OF THE INVESTIGATION

8.1 REVIEW

An examination of existing methods for predicting the effects of land treatment on the flood hydrograph characteristics has revealed some deficiencies. The method developed in this study is based on the Laurenson model and, consequently, seeks to overcome many of these deficiencies. The model attempts to simulate the catchment storage effect and also contains the facility for considering the effects of land treatment in different sub-areas of a catchment.

As applied to the Motueka catchment, the model was distinguished by a number of characteristics. It consisted of a combination of isochronal and sub-catchment approaches, and reproduced the surface runoff hydrograph at the five gauging stations within the catchment. It also contained two notable modifications, namely:

(a) the sub-area structure of the isochronal approach of the Laurenson model was amended so that the model flow pattern more closely resembled the drainage system; and

(b) an optimisation procedure was used to obtain the optimum reservoir delay time-discharge equation for each particular storm.

The two modifications are justified. The modified isochronal approach allows the model to be applied to catchments with complex drainage systems, while the optimisation procedure ensures the best reproduction from the model with the given rainfall excess input data.

In testing the Motueka model no significant difference was detected between the reproductions from the modified isochronal and the sub-catchment approaches. However, on practical grounds the sub-catchment approach is more appealing. It involves much less time in the construction of the sub-areas, and it is more flexible and meaningful for land treatment simulations. Reproduction errors are more likely to occur with the sub-catchment approach, but they should become insignificant in the larger storms and increasing the number of sub-areas should improve the reproductions.

The optimum A and B values, obtained from optimising the reservoir delay time-discharge equation for each of the test storms, varied widely. Besides A and B being interdependent, it appears that their optimum values, or the optimum A/optimum B ratio, increase with increasing storm size. Confirmation of this trend, together with a study of the variation in the optimum A and B values (or their ratio) with catchment parameters, could lead to a relationship that would permit the application of the Laurenson model to ungauged New Zealand catchments.

The sensitivity analyses carried out with the Motueka model demonstrated the technique of determining the hydrological sensitivity of any region of a catchment to land treatment. The sensitivity was expressed in this study by the changes in the surface runoff peak and the quantity of suspended sediment transported over the period of surface runoff. In the course of the analyses it was discovered that the Motueka catchment, although being physically large, is in fact hydrologically small. Thus no conclusion could be reached from this study on the applicability of the Laurenson model to catchments in which storage effects are important.

In performing the sensitivity analyses it was demonstrated that the analysis technique can cope with different forms of land treatment. The only information required is the qualitative effect that the land treatment would have on the loss rate.

The regression equation relating the loss rate with percentage of a catchment in exotic forest was established to quantify the hydrological response of a catchment to afforestation. The predictive use of the equation is not generally recommended, primarily because of the uncertainty arising from the correlation of the exotic forest variable with other variables that are not included in the equation, but which affect the loss rate similarly. Nevertheless, the equation contains essential independent variables, is physically sensible and, statistically, it is highly significant.

8.2 CONCLUSIONS

The main conclusions from the investigation are as follows:

(a) The overall performance of the Motueka model in reproducing surface runoff hydrographs from the five rural catchments within the Motueka was satisfactory. This was notwithstanding inadequacies with the rainfall data.

(b) The Laurenson model, in the modified isochronal or the sub-catchment form and incorporating the optimisation procedure, is a useful catchment management design tool when operated in conjunction with the sensitivity analysis technique. It can be applied to predict the hydrological sensitivity of any region of a catchment to land treatment. It therefore enables the designer to evaluate, where in a catchment, a change in land use would be most effective in producing the desired changes in the flood hydrograph characteristics.

(c) Predicting the actual changes in the flood hydrograph characteristics requires a loss rate-land use relationship. The loss rate equation developed in this study is a good start to fulfilling this objective. However, loss rate behaviour requires further investigation before quantitative predictions can be confidently made.

8.3 RECOMMENDATIONS

To advance the application of the Laurenson model to ungauged catchments and to promote its use in the prediction of the hydrological effects of land-use changes, the following avenues of research are recommended.

(a) Apply the model to a hydrologically large catchment.

(b) Identify the variation in optimum A and B values, or the variation in the ratio of these values, with storm and catchment characteristics.

(c) Investigate the possibility of applying a relationship similar to Equation 3.5, or one that could result from research into (b), to obtain A and B values for individual sub-areas of a catchment.

(d) Examine whether A and B are altered by changes in forest cover and other land uses.

(e) Determine the change in sensitivity analysis curves with storms of different size.

(f) Establish a generally applicable loss rate equation.

(g) Validate a prediction of the hydrological effects of a land-use change.

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APPENDIX A

GEOLOGY AND LAND-USE DETAILS

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TABLE A1

THE ACTUAL GEOLOGY OF THE GEOLOGICAL CLASSES

Probable Infiltration Capacity	Geological Class	Geological Summary	Geological Age
Low	I	Highly indurated, generally fine-grained sediments and minor metavolcanics	Paleozoic
	II	Ultramafic intrusives	"
	III	Massive granites	"
	IV	Dense volcanics and volcanic conglomerates	"
	V	Well-indurated, generally fine-grained sediments	Upper Paleozoic and Triassic
	VI	Moderately indurated, muddy sediments	Tertiary
High	VII	Weathered, unconsolidated gravels	Recent Quarternary

TABLE A2

BREAKDOWN OF THE GEOLOGICAL CLASSES IN EACH CATCHMENT

Geological Class	Percentage of a catchment in a geological class						
	Upper Motueka	Wangapeka	Baton	Minor Woodstock	Woodstock	Minor Motueka	Motueka
I		56.22	60.32	0.82	17.69	37.47	20.35
II	31.66				10.95		9.48
III		26.54	1.39	13.11	5.36	53.67	11.84
IV		8.80	18.32		1.87		1.62
V	68.34			3.39	8.51		7.37
VI		8.44	14.17	5.11	7.93		6.87
VII			5.80	77.57	47.69	8.86	42.47
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

TABLE A3

BREAKDOWN OF THE LAND USES IN EACH CATCHMENT

Land Use	Percentage of a catchment in a land use						
	Upper Motueka	Wangapeka	Baton	Minor Woodstock	Woodstock	Minor Motueka	Motueka
Exotic Forest	0.74			24.18	14.75	14.30	14.69
Native Forest	43.90	71.77	72.71	21.83	38.91	24.03	36.92
Fern		12.40	6.11	22.10	16.48	26.76	17.85
Scrub				0.45	0.27	1.85	0.49
Grass			3.15	14.65	9.22	12.95	9.72
Bare Ground	55.36	15.83	18.03	16.79	20.37	20.11	20.33
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

APPENDIX B

MODEL DETAILS

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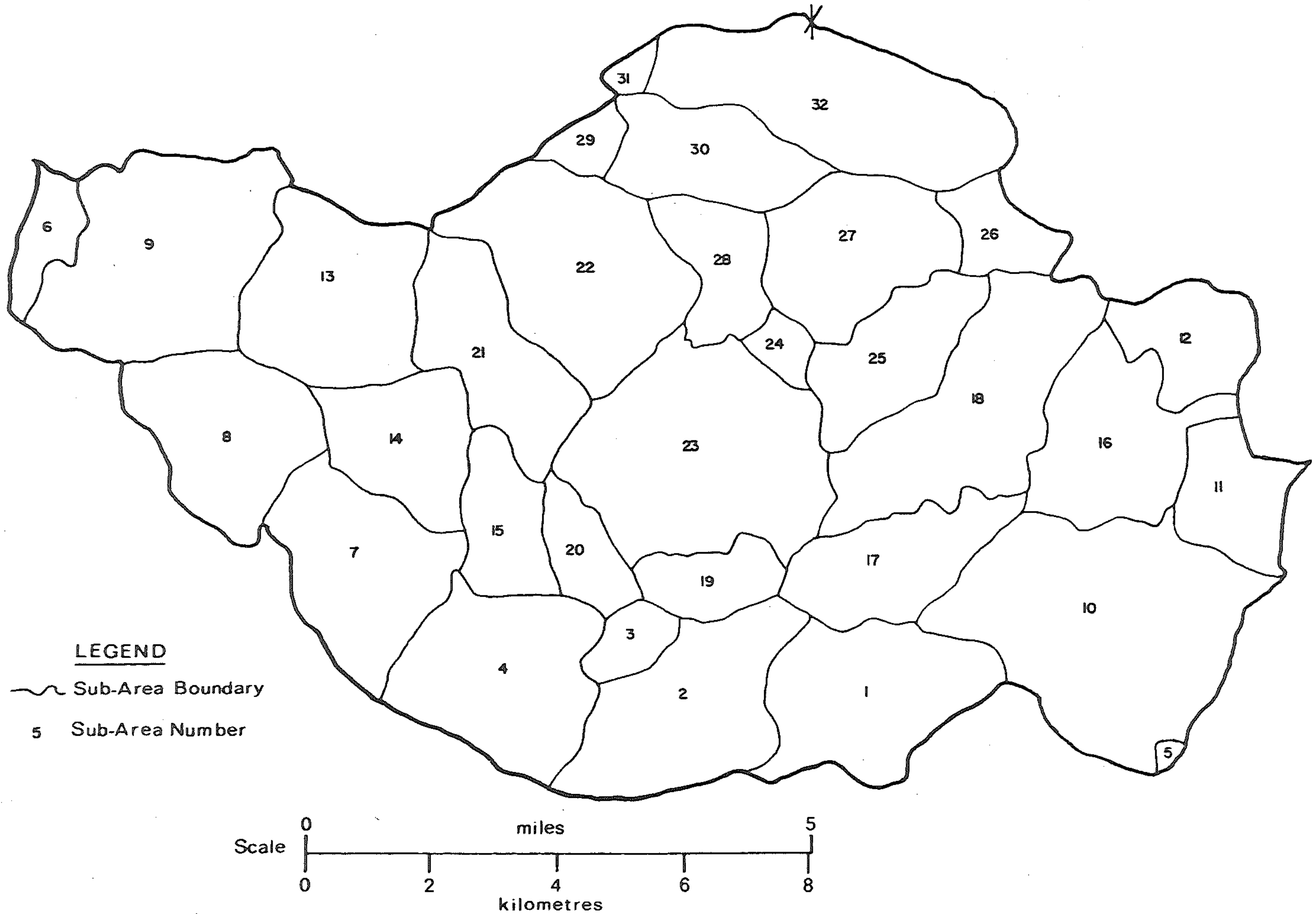

FIG. B1: UPPER MOTUEKA MODEL — Sub-Area Pattern

Sub-Area	Area of the sub-area, in sq. miles	Relative travel time from the sub-area reservoir to the Upper Motueka gauging station	The sub-areas contributing to the sub-area concerned
1	2.75	0.950	
2	2.84	0.850	1
3	0.47	0.812	
4	2.93	0.750	2 3
5	0.07	0.701	
6	0.64	0.740	
7	2.64	0.650	4
8	2.49	0.650	
9	3.88	0.650	6
10	5.31	0.650	5
11	1.27	0.630	
12	1.27	0.630	
13	2.77	0.550	9
14	1.76	0.550	7 8
15	1.19	0.520	
16	2.35	0.550	10 11 12
17	1.84	0.512	
18	3.43	0.450	16 17
19	0.88	0.410	
20	0.78	0.418	
21	2.11	0.450	13 14 15
22	3.46	0.350	21
23	4.43	0.350	19 20
24	0.33	0.320	
25	1.65	0.350	18
26	0.77	0.314	
27	2.31	0.250	25 26
28	1.18	0.250	22 23 24
29	0.41	0.213	
30	1.71	0.150	27 28 29
31	0.18	0.104	
32	3.64	0.050	30 31

$\underline{Y = 0.512}$

FIG. B2: UPPER MOTUEKA MODEL - SUB-AREA AND TRAVEL TIME DETAILS

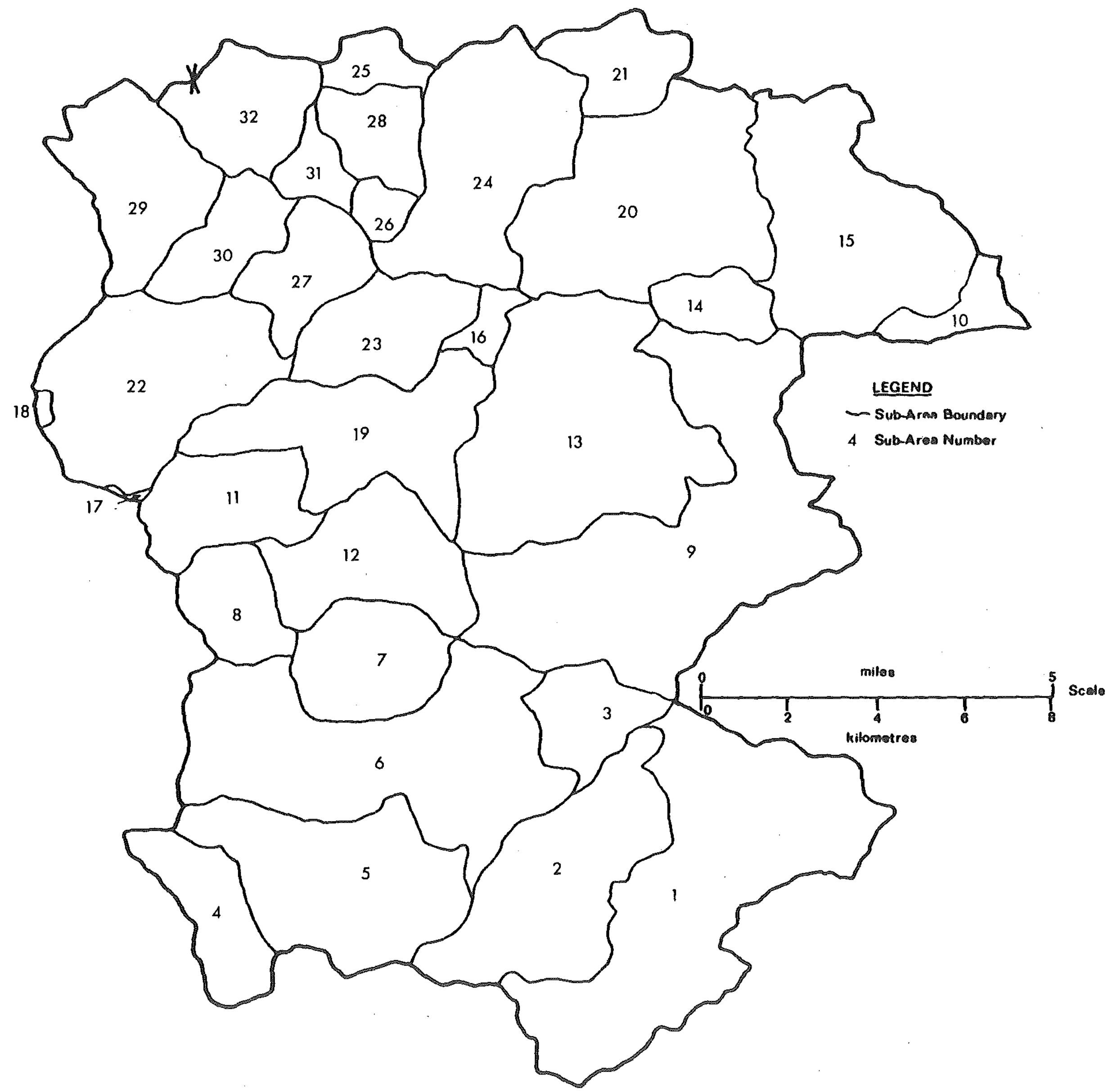

FIG. B3: WANGAPEKA MODEL - Sub-area pattern

Sub-Area	Area of the sub-area, in sq. miles	Relative travel time from the sub-area reservoir to the Wangapeka gauging station	The sub-areas contributing to the sub-area concerned
1	11.61	0.950	
2	6.35	0.850	1
3	2.06	0.830	
4	2.50	0.917	
5	6.49	0.850	4
6	10.15	0.750	2 3 5
7	3.16	0.650	6
8	2.06	0.608	
9	12.93	0.650	
10	1.09	0.609	
11	3.12	0.522	
12	4.04	0.550	7 8
13	9.68	0.550	9
14	1.38	0.507	
15	7.39	0.550	10
16	0.62	0.507	
17	0.06	0.401	
18	0.11	0.401	
19	5.55	0.450	11 12 13 16
20	8.24	0.450	14 15
21	2.08	0.420	
22	6.69	0.350	17 18
23	3.06	0.350	19
24	6.52	0.350	20 21
25	0.97	0.307	
26	0.58	0.304	
27	2.36	0.250	22 23
28	1.79	0.250	24 25 26
29	4.13	0.133	
30	2.11	0.150	27
31	0.92	0.150	28
32	2.90	0.050	29 30 31

$\underline{Y = 0.570}$

FIG. B4: WANGAPEKA MODEL - SUB-AREA AND TRAVEL TIME DETAILS

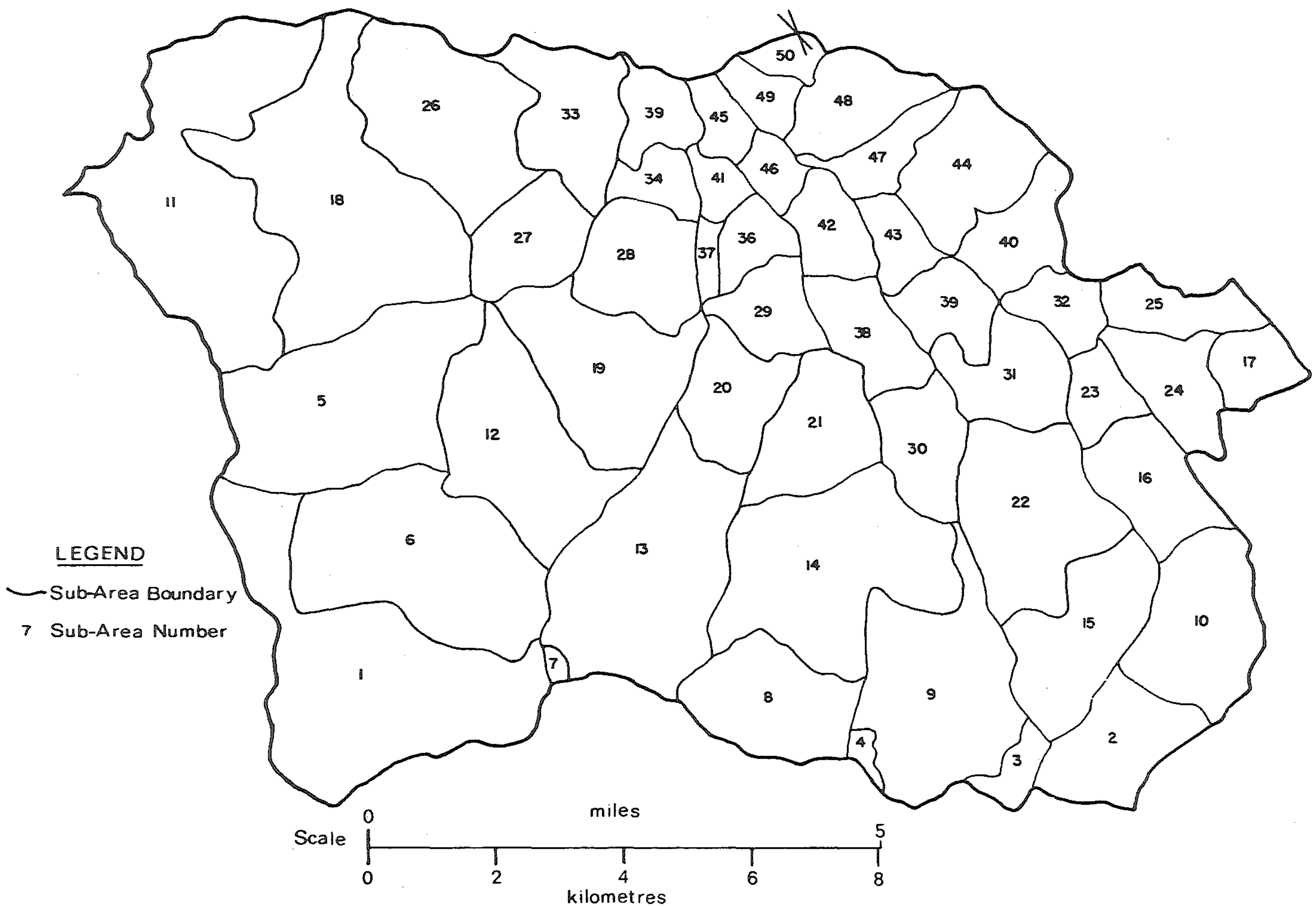

FIG. B5 : BATON MODEL — Sub-Area Pattern

Sub-Area	Area of the sub-area, in sq. miles	Relative travel time from the sub-area reservoir to the Baton gauging station	The sub-areas contributing to the sub-area concerned
1	4.42	0.950	
2	1.27	0.923	
3	0.30	0.905	
4	0.11	0.901	
5	3.33	0.850	
6	3.35	0.850	1
7	0.07	0.802	
8	1.58	0.823	
9	2.75	0.850	3 4
10	1.82	0.850	2
11	4.45	0.737	
12	2.45	0.750	5 6
13	3.40	0.750	7
14	3.27	0.750	8 9
15	1.75	0.742	
16	1.11	0.750	10
17	0.60	0.709	
18	4.17	0.650	11
19	2.10	0.650	12
20	1.10	0.650	13
21	1.35	0.650	14
22	2.29	0.650	15
23	0.51	0.650	16
24	0.94	0.650	17
25	0.73	0.633	

FIG. B6: BATON MODEL - SUB-AREA AND TRAVEL TIME DETAILS
(continued next page)

Sub-Area	Area of the sub-area, in sq. miles	Relative travel time from the sub-area reservoir to the Baton gauging station	The sub-areas contributing to the sub-area concerned
26	2.50	0.550	18
27	0.94	0.526	
28	1.29	0.550	19
29	0.77	0.550	20 21
30	0.98	0.525	
31	1.08	0.550	22
32	0.55	0.550	23 24 25
33	1.44	0.450	26 27
34	0.46	0.450	28
35	0.61	0.350	33 34
36	0.47	0.450	29
37	0.17	0.414	
38	0.89	0.450	30
39	0.73	0.450	31
40	0.88	0.450	32
41	0.30	0.350	36 37
42	0.67	0.350	38
43	0.48	0.350	39
44	1.44	0.350	40
45	0.38	0.250	35 41
46	0.34	0.250	42
47	0.59	0.250	43 44
48	1.05	0.150	47
49	0.40	0.150	45 46
50	0.27	0.050	48 49

$\underline{Y = 0.673}$

FIG. B6 Contd.: BATON MODEL - SUB-AREA AND TRAVEL TIME DETAILS

Sub-Area	Area of the sub-area, in sq. miles	Relative travel time from the sub-area reservoir to Woodstock	The sub-areas contributing to the sub-area concerned
1		0.805*	
2		0.516*	
3		0.156*	
4	41.52	0.893	
5	41.59	0.918	
6	36.75	0.774	1
7	49.40	0.681	4 5
8	34.10	0.708	
9	30.59	0.648	
10	24.95	0.615	6
11	29.93	0.418	7 8 10
12	24.96	0.286	
13	18.00	0.441	2 9
14	27.90	0.190	
15	50.44	0.037	3 11 12 13 14

$\underline{Y = 0.575}$ (for the Woodstock catchment)

* Relative travel time from the *outlet* of the sub-area, i.e. from the gauging station of the Upper Motueka, Wangapeka or Baton catchment.

FIG. B7: MINOR WOODSTOCK MODEL - SUB-AREA AND TRAVEL TIME DETAILS

Sub-Area	Area of the sub-area in sq. miles	Relative travel time from the sub-area reservoir to Bluegum Corner	The sub-areas contributing to the sub-area concerned
15		0.422*	
16	15.22	0.412	
17	10.18	0.374	15 16
18	15.43	0.353	
19	34.97	0.286	17 18
20	28.91	0.161	19

<u>Y = 0.691</u> (for the Motueka catchment)

* Relative travel time from the *outlet* of the sub-area, i.e. from Woodstock.

FIG. B8: MINOR MOTUEKA MODEL - SUB-AREA AND TRAVEL TIME DETAILS

APPENDIX C

COMPUTER PROGRAMS

C.1 INTRODUCTION

The computer programs written for this investigation are described briefly in the next section. Because of the length of some of the programs it was impractical to include them in this text (the Motueka model program alone is 72 computer pages long). However, the programs are available in listing and card-deck form from the Computer Program Library, Civil Engineering Dept., University of Canterbury.

The programs were written in Fortran IV language for the University's IBM 360/44 computer, which has since been superseded by a Burroughs B6718 computer. The plotting subroutines called in some of the programs refer to a program package that controlled, through a PD11 computer, the plotting of graphs by the University's Calcomp plotter. Most programs were kept in a general form and are applicable to single catchments.

In some cases the program core storage requirements exceeded the allowable limit of 128K bytes. For such a program it was necessary to store the data arrays on discs and to arrange the program in phases. The associated direct accessing operations and the phase conversions increased the program execution time, sometimes appreciably. For example, before the routing of the hydrograph tail was amended (Section 7.1.4), the routing of rainfall excess through a constituent model with the Motueka model program took more than 1½ seconds per sub-area. Thus the routing of one storm through the Baton model, for instance, took approximately

80 seconds. This in turn meant that the time taken in optimising a routed hydrograph from this one model was in the order of an hour. However, these execution times would be reduced considerably if such programs were adapted to the later generation computers, which are faster and have greater core storage.

C.2 THE PROGRAMS

C.2.1 Relative Travel Times

Program RETFLO computes the relative travel times for points in a catchment. The main input data are the flow distances between the contours and the contour intervals. The flow distances between the points on a flow path are accumulated, so that only the flow distances between one point and the next, plus the uniform contour interval, are required as input for a point.

C.2.2 Hydrograph Analysis

(a) Program COGTOD interpolates from a stage-discharge rating curve to convert a stage hydrograph to a discharge hydrograph. The stage hydrograph ordinates can be read in at irregular time intervals and in no chronological order. The discharge hydrograph ordinates are obtained at hourly intervals in proper chronological order. A plot of the finished product is optional.

(b) Program HGRAPH was used to separate the individual surface runoff hydrographs from the total runoff hydrographs. It divides the separation process into twelve possible steps, with it being necessary to rerun the program for each step. The plot output from a run shows results of that step. The plots facilitate the definitions of the time limits of the streamflow components. The plot from the final step shows the separated surface runoff hydrographs.

(c) Program RECESS supplements HGRAPH - it plots the master recession curve of a streamflow component, given the hourly depletion ratio (k_r).

C.2.3 Rainfall Analysis

Program DELAD processes and manipulates the rainfall, producing necessary input data for the Motueka model program. A feature of the program is that it takes account of areal and temporal variations in rainfall. Given the basic rainfall and streamflow data, the program performs the following operations:

(a) determines rainfall and rainfall excess hyetographs for all the sub-areas in a catchment;

(b) derives a constant loss rate;

(c) quantifies various rainfall and rainfall excess characteristics; and

(d) computes the lag and mean discharge for a storm.

For a series of storms run in succession the program also gives a least-squares solution of the lag-mean discharge relationship, in the form of Equation 3.7, for two forms of mean discharge ($\bar{q}_T$ and $\bar{q}_{TS}$).

C.2.4 Motueka Model

Program RURMOT was designed specifically to carry out the Motueka model operations and the various sensitivity analyses. However, it will perform the same functions for a single catchment, with there being no restriction on the model sub-area pattern nor on the sub-areas to be used in a sensitivity analysis. A plot is obtainable of the routed hydrograph (before and after optimisation) and the corresponding actual hydrograph.

APPENDIX D

RESULTS, STORMS AND TREATMENT LOCATIONS

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STORM		UPPER MOTUEKA		WANGAPEKA		BATON		WOODSTOCK		MOTUEKA	
No.	Date	L	$\bar{q}_{TS}$	L	$\bar{q}_{TS}$	L	$\bar{q}_{TS}$	L	$\bar{q}_{TS}$	L	$\bar{q}_{TS}$
5	28-29/10/70*	7.78	1177	12.66	3349	10.50	1593	14.87	6805	17.07	7838
6	23-24/9/70	10.84	1212	12.13	6601	9.28	1934	15.22	11169	17.50	11614
7	16-17/9/70	-	-	10.29	6637	7.93	2315	14.73	14611	17.61	17049
8	10-12/9/70	8.44	2460	13.96	4836	10.22	2165	16.43	18338	20.93	18825
9	8-9/9/70	9.50	609	8.53	4314	7.16	1350	11.61	6999	15.86	6731
10C	30-31/8/70	-	-	12.73	7224	11.05	1879	14.07	18331	17.07	19120
11A	20-21/8/70	11.87	367	13.01	1710	10.69	1514	15.82	3223	18.93	3510
13	2-4/7/70	13.02	1182	15.48	3717	15.48	1539	22.28	14837	25.30	16435
14	2-3/6/70	10.02	1258	11.78	2322	8.20	889	17.70	6818	18.34	7412
18A	24-25/12/69*	8.71	263	13.79	3302	10.95	605	16.64	4151	19.70	3571
18B	25-26/12/69*	12.53	327	11.97	4590	10.68	1796	16.05	6578	18.63	6541
19	16-18/12/69*	13.26	922	13.20	5285	10.98	3023	16.60	11568	19.40	14679
20A	30/11-1/12/69*	12.27	783	15.26	1051	17.39	299	21.05	3169	25.73	2919
21	24-25/9/69	13.32	519	15.62	2151	11.15	2042	14.12	5899	17.62	8365
24	9-11/9/69	9.11	3808	18.42	4800	9.98	1860	19.05	16636	23.40	18423
25	24-25/7/69	18.10	124	8.30	1631	11.56	1176	11.91	3002	15.50	3472

* A summer storm referred to in Section 6.1.

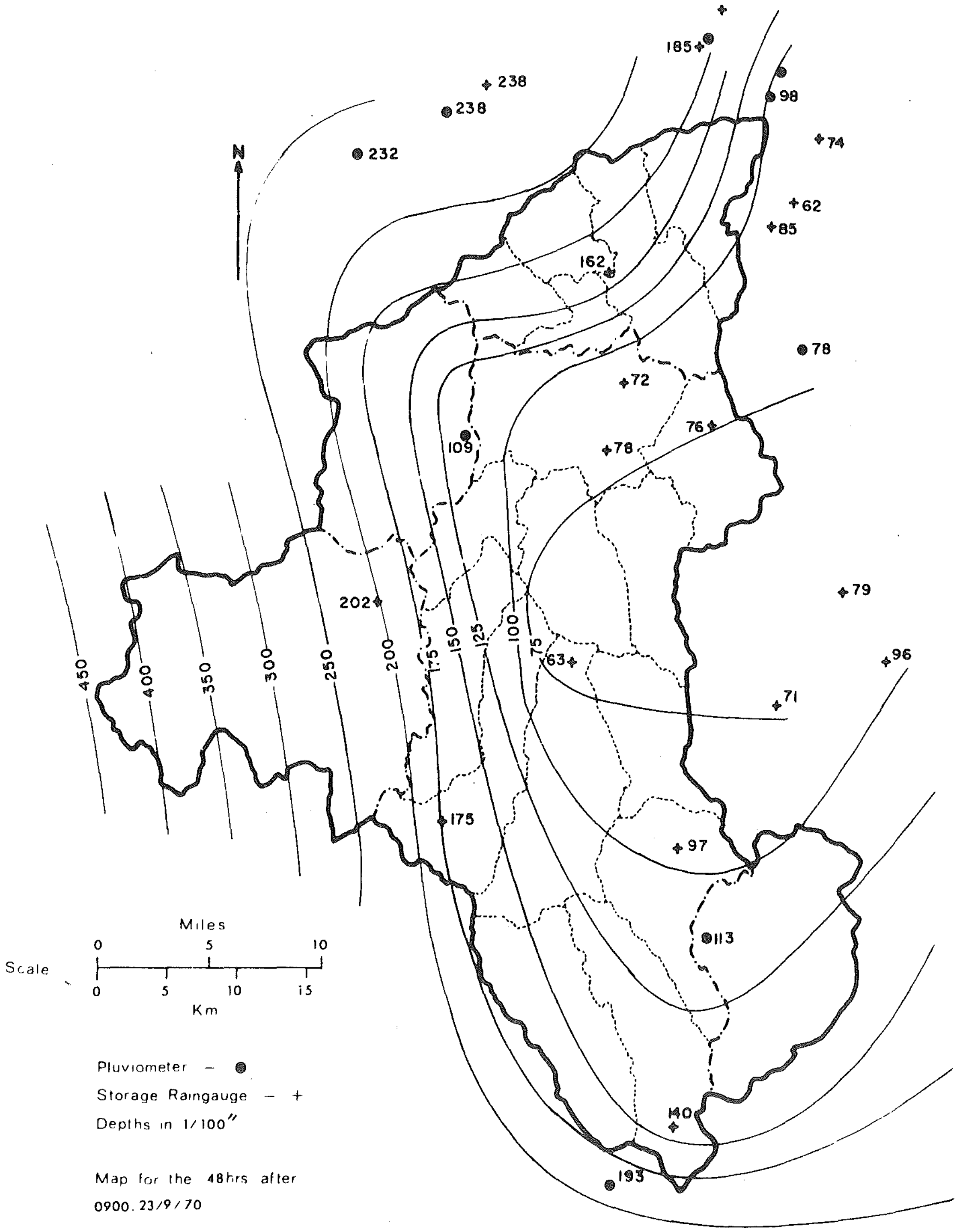

FIG. D2: STORM NO. 6 - ISOHYETAL MAP

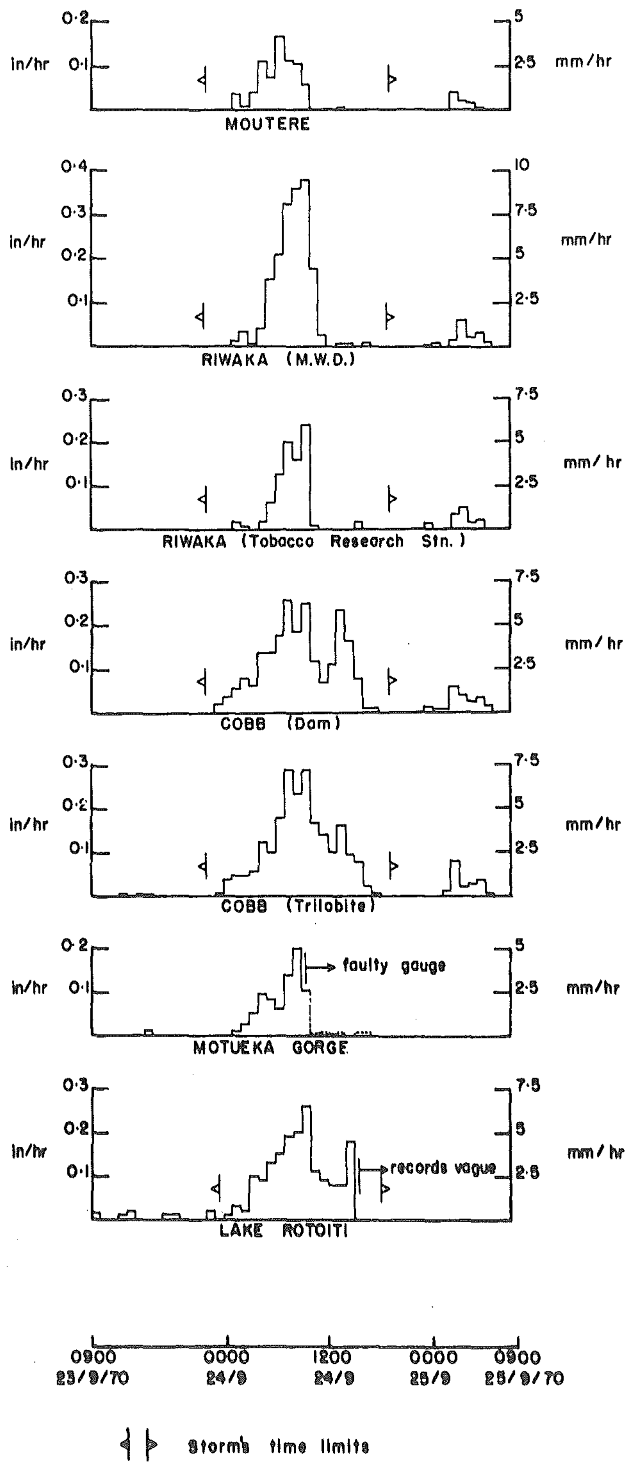

FIG. D3: STORM NO. 6 - THE PLUVIOMETER HYETOGRAPHS

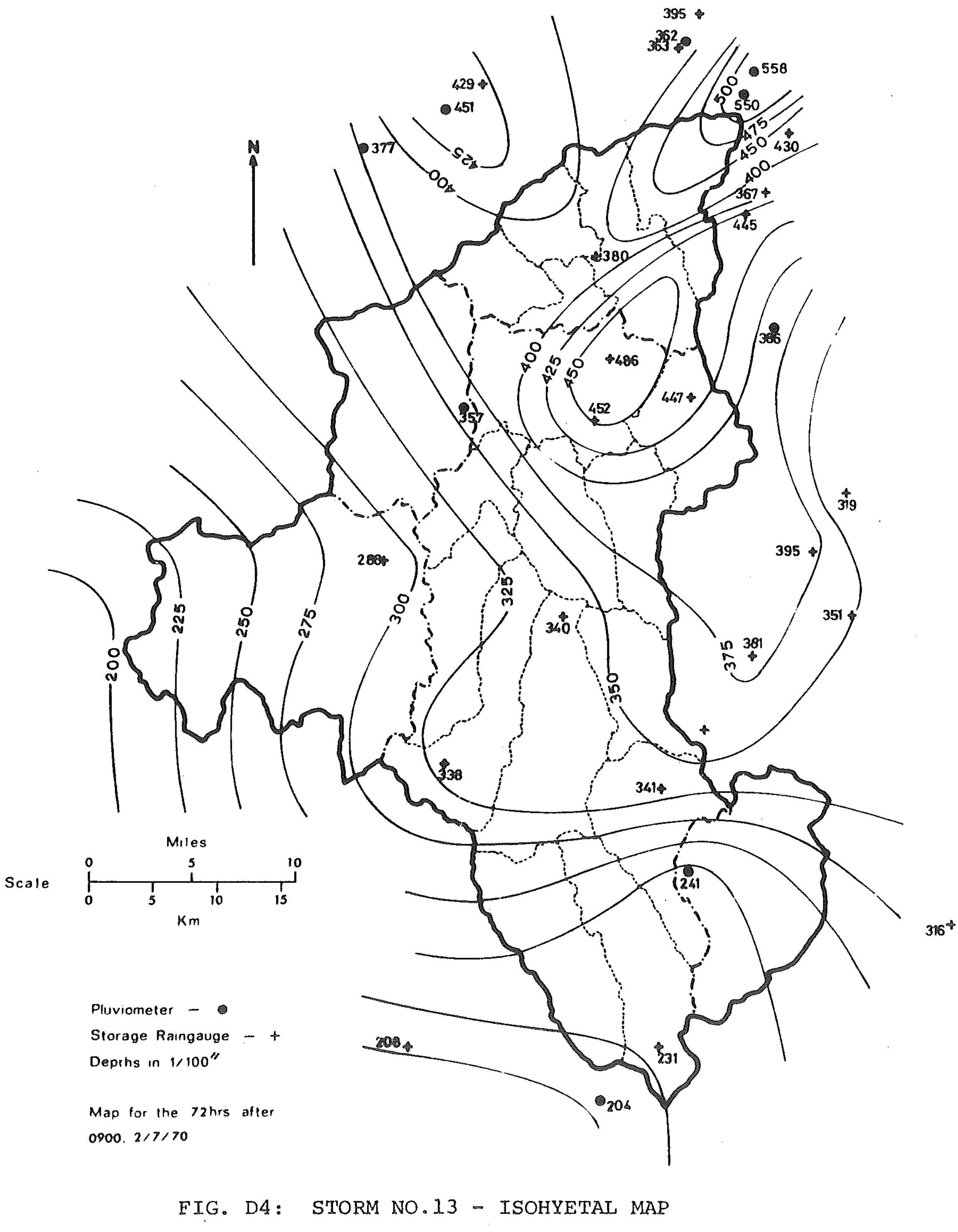

FIG. D4: STORM NO.13 - ISOHYETAL MAP

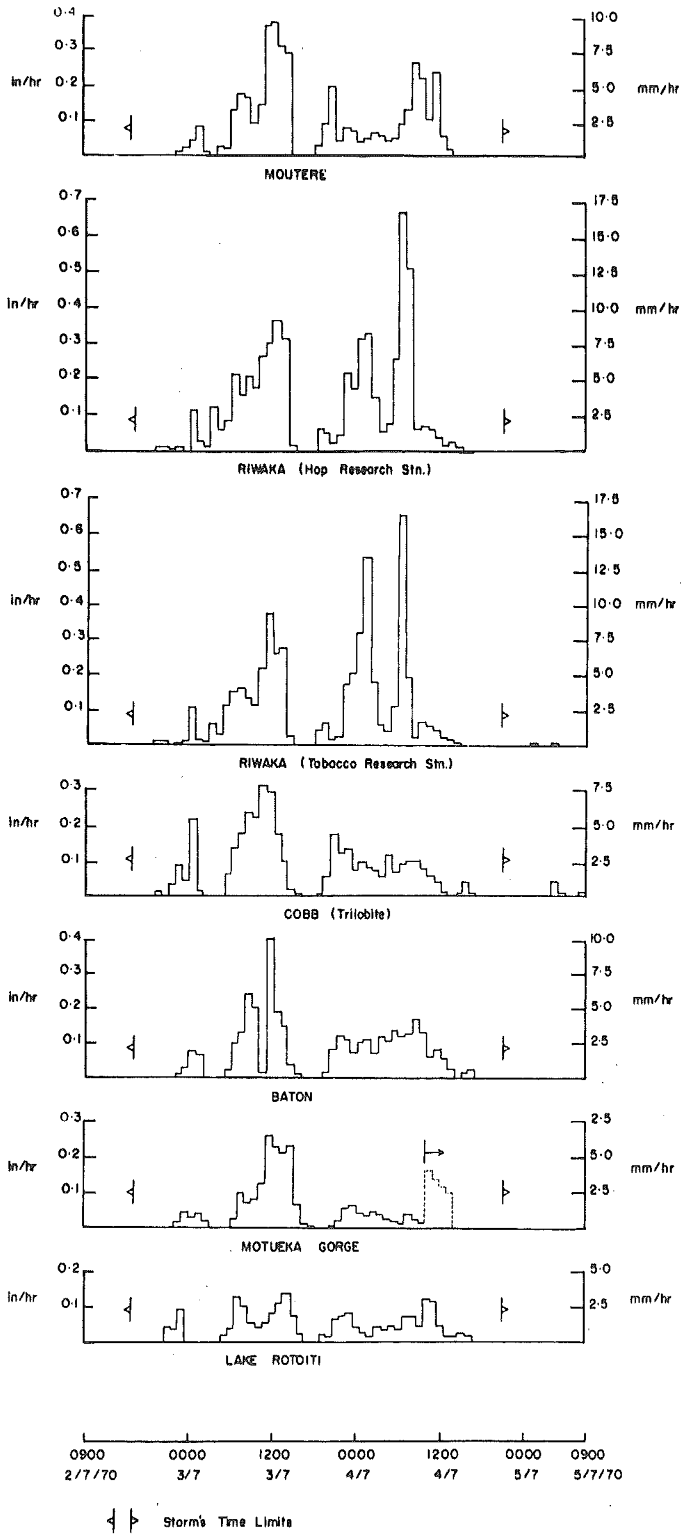

FIG. D5 : STORM No. 13 — THE PLUVIOMETER HYETOGRAPHS

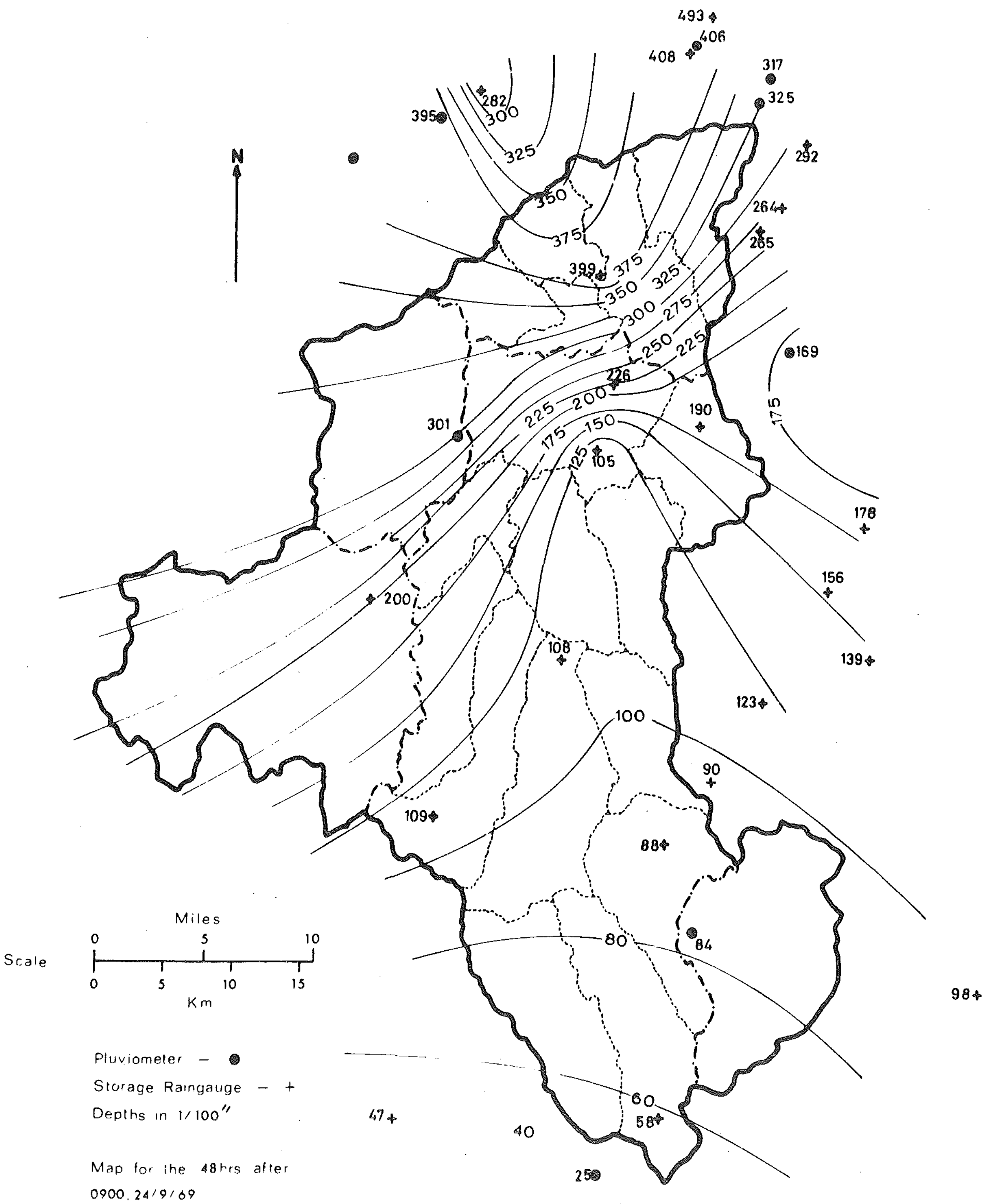

FIG. D6: STORM NO.21 - ISOHYETAL MAP

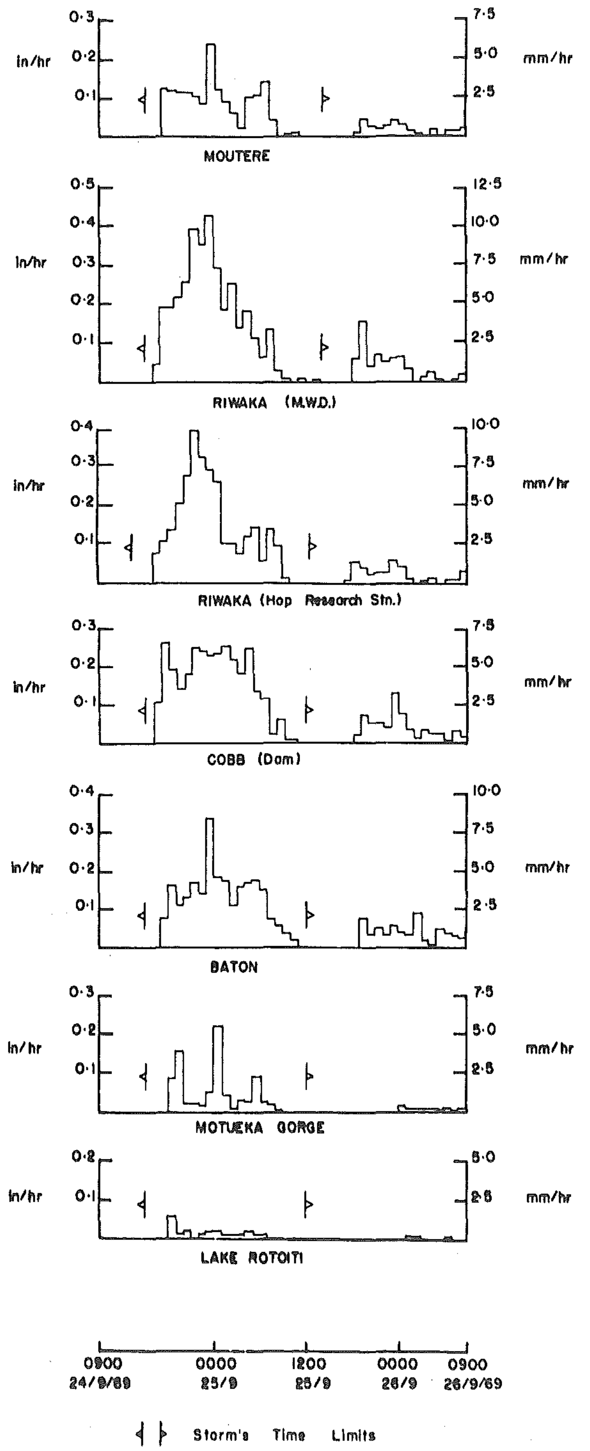

FIG. D7 : STORM No. 21 — THE PLUVIOMETER HYETOGRAPHS

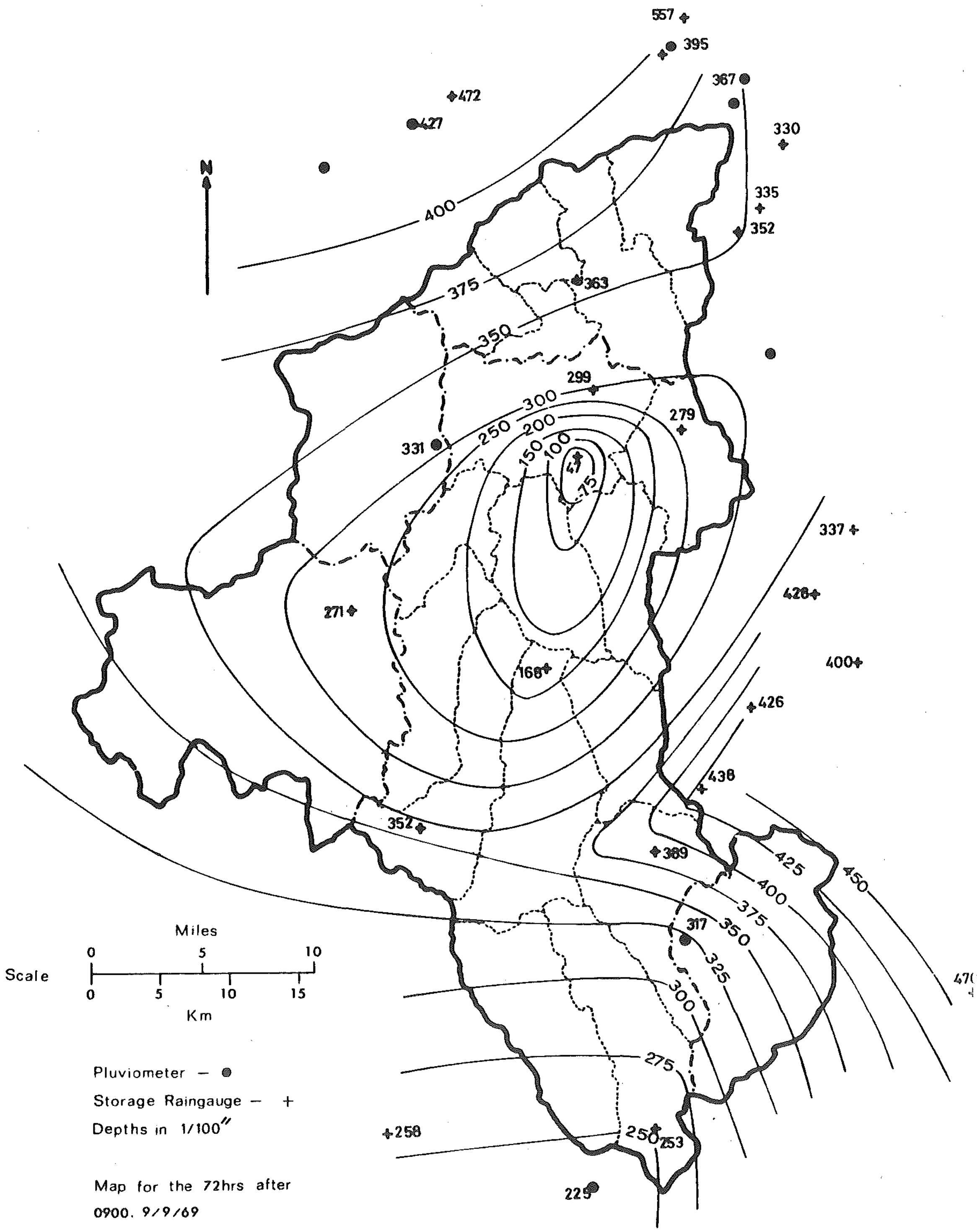

FIG. D8: STORM NO.24 - ISOHYETAL MAP

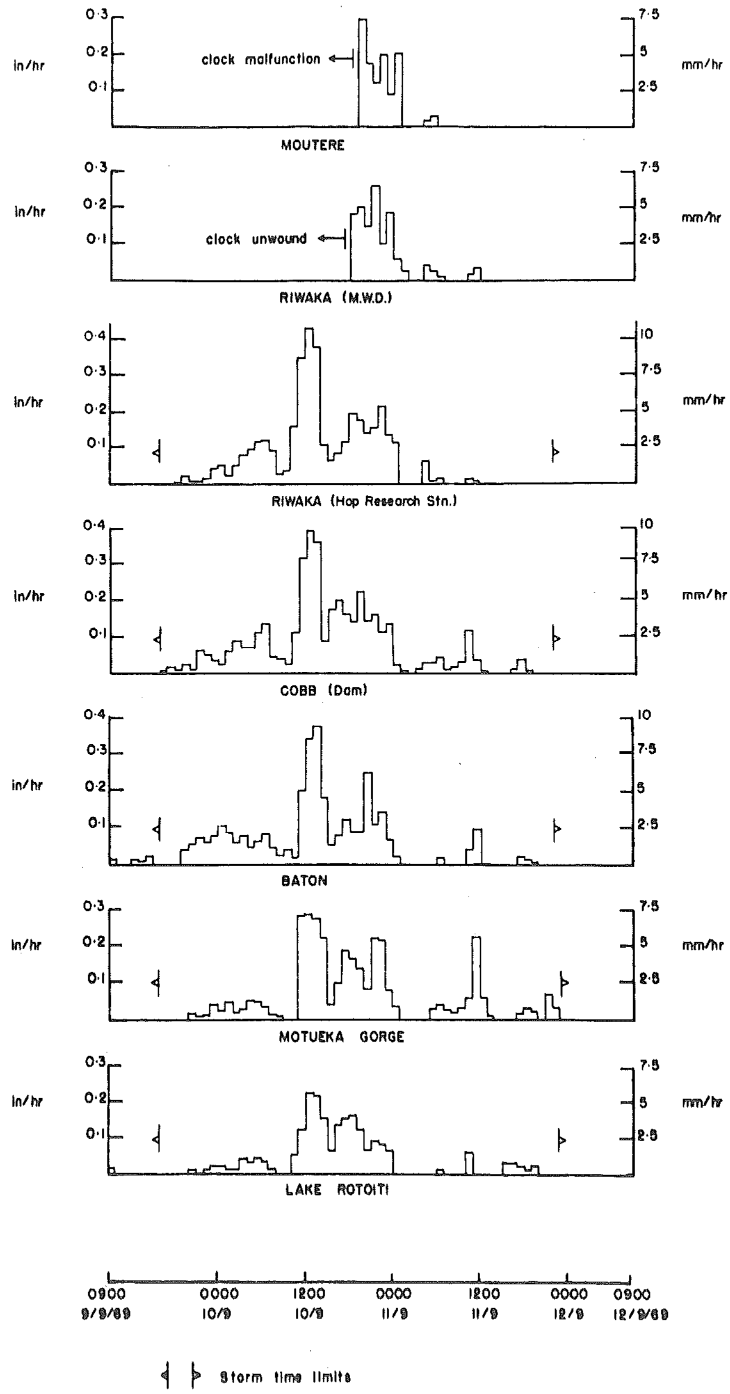

FIG. D9 : STORM No.24 — THE PLUVIOMETER HYETOGRAPHS

	Constituent Model				
	Upper Motueka	Wangapeka	Baton	Minor Woodstock	Minor Motueka
<u>Storm No.6</u>					
A	126.5	145.6	33.7	43.4	4419
B	0.438	0.345	0.235	0.254	0.649
Efficiency	0.876	0.955	0.875	0.973	0.921
Integral Square Error	5.56%	3.08%	5.30%	2.38%	3.59%
"Correlation Coefficient"	0.965	0.988	0.969	0.993	0.981
Coefficient of Variation	0.393	0.220	0.340	0.175	0.273
Variation in S.R. Peak	-20.6%	11.6%	15.1%	-11.6%	-20.5%
<u>Storm No.13</u>					
A	411.2	196.8	394.7	103.4	210.5
B	0.563	0.344	0.572	0.218	0.245
Efficiency	0.837	0.886	0.750	0.728	0.886
Integral Square Error	4.23%	2.92%	4.63%	4.63%	2.88%
"Correlation Coefficient"	0.965	0.979	0.949	0.941	0.977
Coefficient of Variation	0.346	0.258	0.403	0.444	0.277
Variation in S.R. Peak	-12.5%	-4.1%	20.1%	-25.8%	-16.8%
<u>Storm No.21</u>					
A	18.5	38.8	54.4	7.65	135.4
B	0.046	0.143	0.281	0.013	0.298
Efficiency	0.786	0.978	0.680	0.982	0.647
Integral Square Error	5.86%	1.63%	7.31%	1.53%	7.07%
"Correlation Coefficient"	0.959	0.996	0.926	0.996	0.923
Coefficient of Variation	0.361	0.114	0.507	0.108	0.505
Variation in S.R. Peak	-31.5%	3.1%	37.1%	-2.7%	-30.9%
<u>Storm No.24</u>					
A	65.7	214.8	60.0	97.5	202.0
B	0.285	0.337	0.281	0.242	0.280
Efficiency	0.803	0.708	0.510	0.976	0.968
Integral Square Error	5.16%	4.99%	9.44%	1.53%	1.66%
"Correlation Coefficient"	0.944	0.940	0.877	0.994	0.993
Coefficient of Variation	0.497	0.441	0.661	0.146	0.165
Variation in S.R. Peak	-3.9%	25.3%	14.6%	-1.4%	-6.4%

FIG. D10: DETAILS OF THE OPTIMUM ROUTED SURFACE RUNOFF HYDROGRAPHS IN FIGURES 6.2-6.9

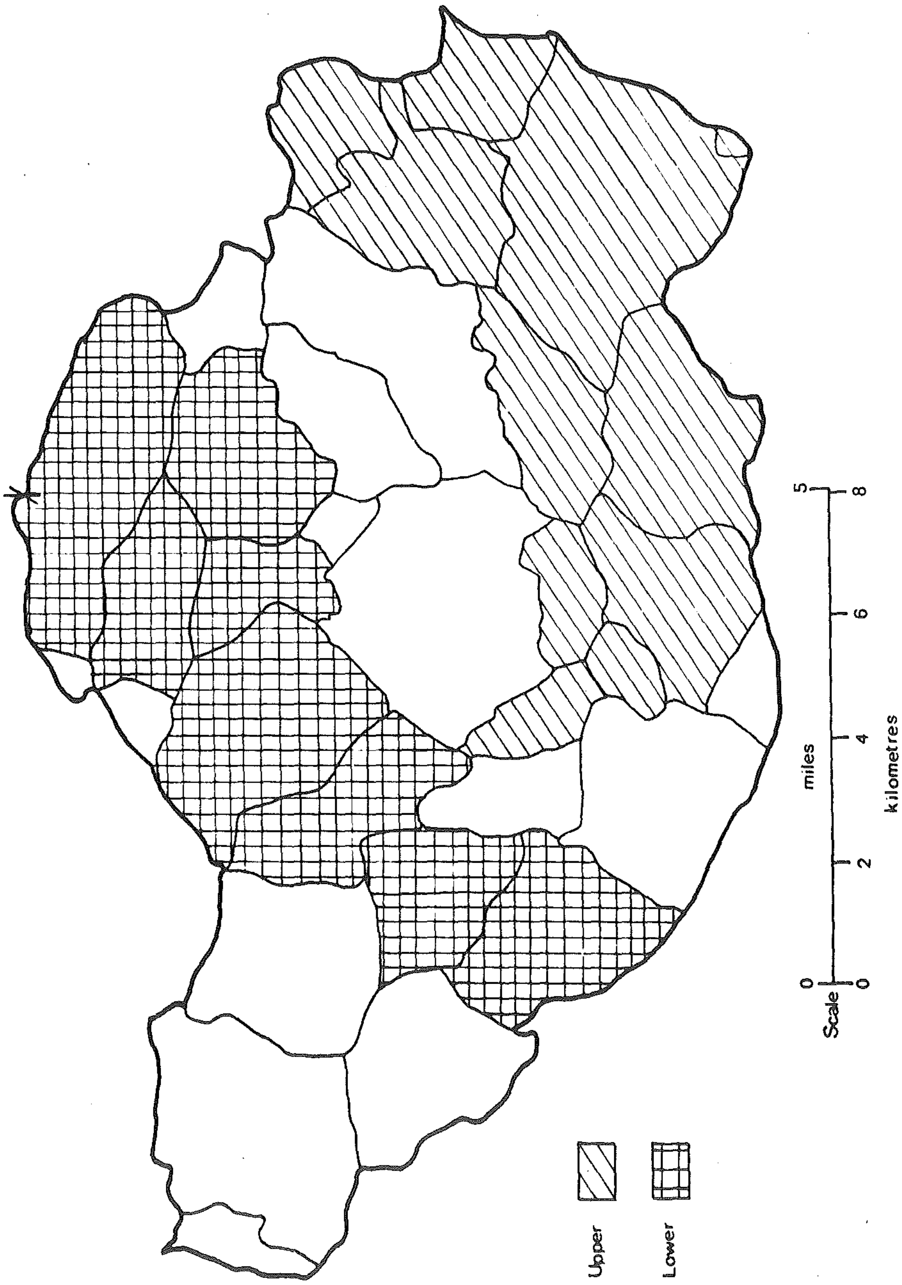

FIG. D11 : UPPER MOTUEKA CATCHMENT — Locations of land treatment regions

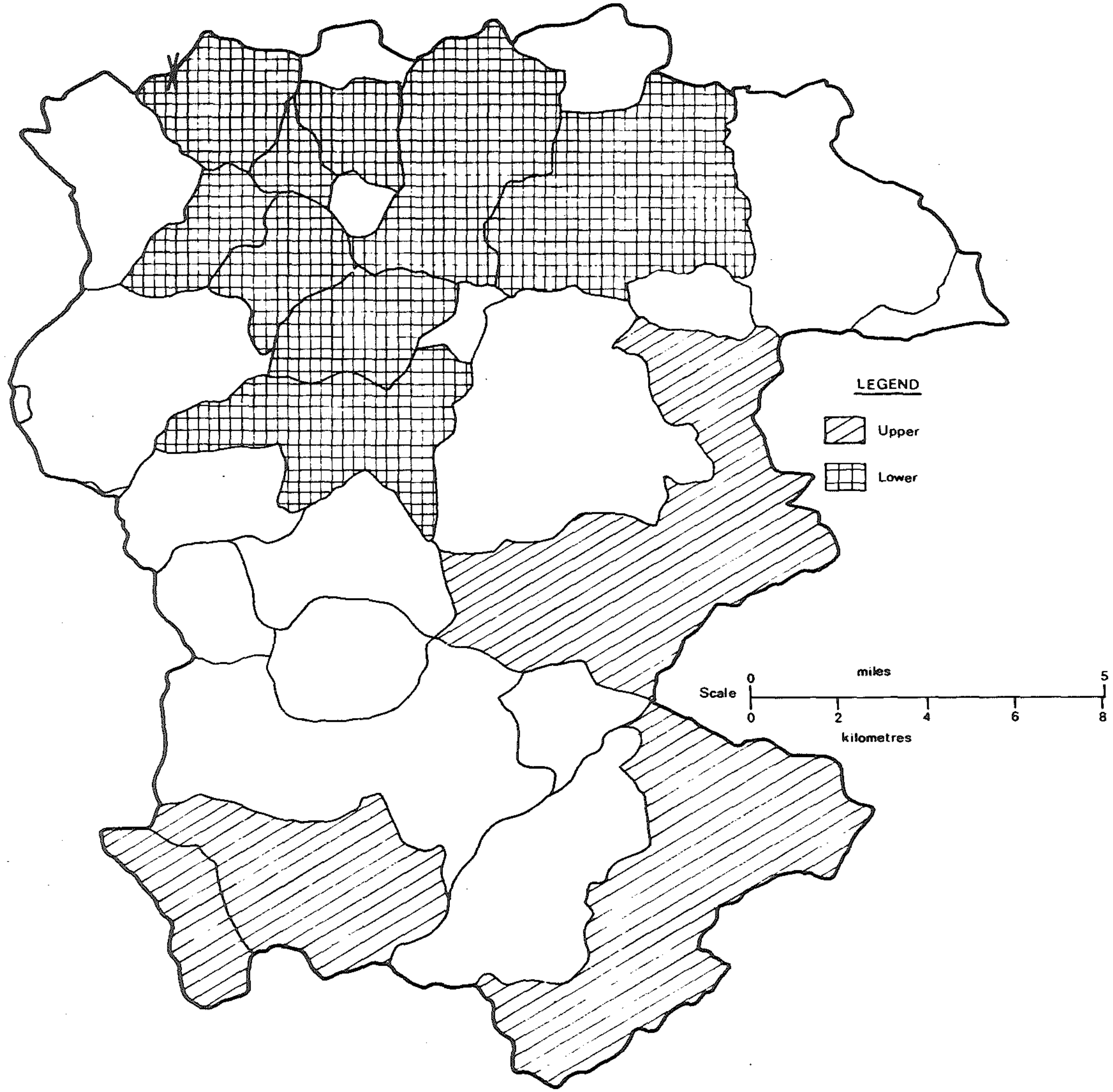

FIG. D12: WANGAPEKA CATCHMENT - Locations of land treatment regions

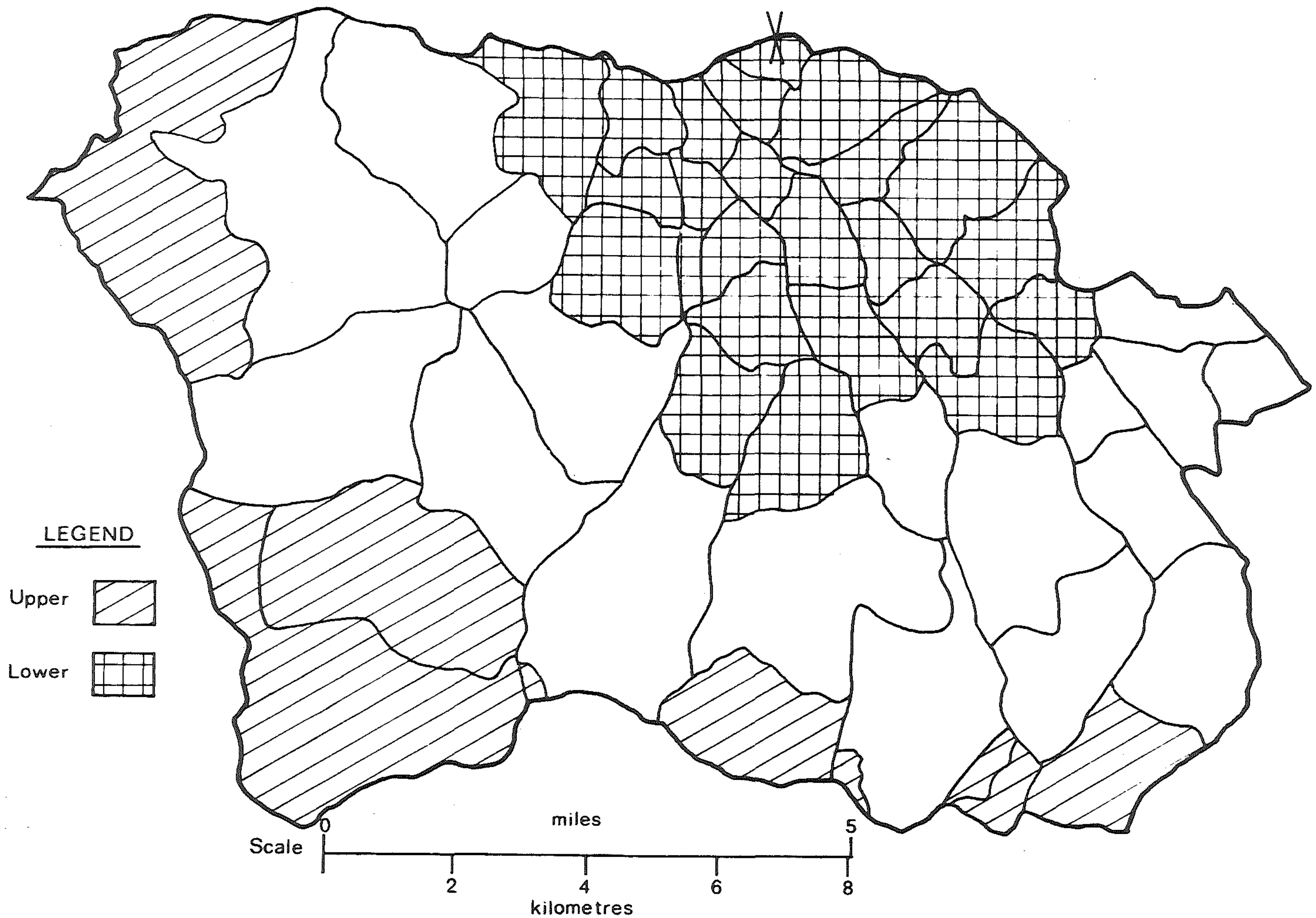

FIG. D13 : BATON CATCHMENT – Locations of land treatment regions